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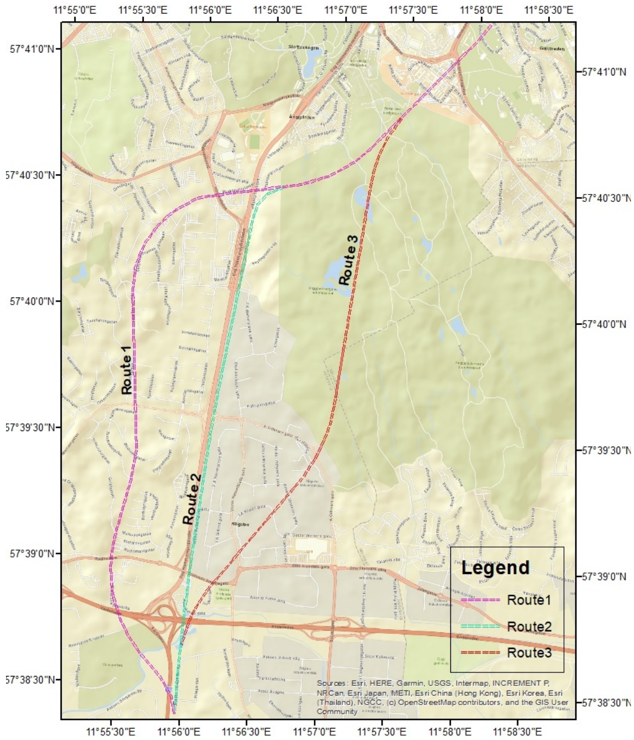

Multi-criteria analysis of alternative tunnel corridors in Göteborg

A geosystem services perspective

Master's thesis in Master Program in Infrastructure and Environmental Engineering (MPIEE)

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Cover: GIS based map of three possible railway routes. Stretches are included in the city of Gothenburg's plan.

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Abstract

The comprehensive plan of Gothenburg's municipality, Sweden suggests to extend the railway network in the southern part of the city. There exist three potential railway routes, some of which pass through underground tunnels. This report specifically investigates all three tunnel routes, focusing on the subsurface resources. The evaluation is centered on geo-system services along the tunnel corridors, a novel concept that elucidates the resources and services available for human utilization beneath the surface. geo-system services can be categorized into four distinct groups: supporting, cultural, regulating, and provisioning. Initially, an assessment is conducted to evaluate the current quality of these geo-system services and their potential for exploitation.

Additionally, any potential conflicts that could have adverse effects on these attributes are examined as part of this evaluation, with Geographic Information Systems (GIS) serving as a key tool in the assessment process. The process utilized for this study is multi-criteria analysis. All three tunnel routes are poised to have a great impact on different geo-system services. The services at high risk are geo-energy wells, groundwater resources, and the mobilizing of pollutants.

However, in some parts, the excavation could synergistically extract geo-material through tunnel corridors. But a comparative study is needed to facilitate comprehensive decision-making. Such a study would compare impacts of potential routes on geo-system services. Careful consideration is required to balance extraction benefits against impacts to other underground services and systems. The comparative study aims to support route selection by assessing how alignments may positively or negatively affect the geo-system. This ensures the most suitable choice weighing all relevant factors.

Keywords: Geo-system services, Subsurface, GIS, Multi-criteria analysis.

Acknowledgements

This master's thesis was completed at Chalmers University of Technology in the Department of Architecture and Civil Engineering from January 2023 to March 2024. The thesis is worth 30 credits. The thesis intends to create a roadmap for selecting the best tunnel corridor with the least impact on geo-system services using risk assessment and decision support criteria.

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Abdul Rehman, Gothenburg, 2024

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Introduction

1.1 Background

The benefits that humans derive from the subsurface are known as geosystem services (GS) (Frisk et al., 2022). These include the use of the subsurface for building and construction both inside and outside of it, the extraction of groundwater, energy, and materials, the storing of resources like water, energy, and carbon dioxide, the provision of habitat for ecosystems and support for surface life, and the preservation of cultural and geological heritage. Sustainable management of the subsurface is hampered by sectorial management, which promotes the first-come-first-served approach without careful consideration of competing or complementing subsurface uses (de Mulder et al., 2012). This affects inter-generational equity.

Geosystem services, such as clean water, natural resources, and climate regulation, are advantages that humans obtain from the subsurface. These services are essential to the planning and decision-making process for sustainable municipal planning, particularly when it comes to subterranean development (Bartel, 2016).

Finally, taking into account the potential effects on the city's geosystem, this analysis will offer useful insights for decision-makers about the selection of the most viable and sustainable tunnel corridor for Gothenburg's railway infrastructure.

The subsurface may also contain significant artifacts and locations that contribute to our understanding of the history of the planet, such as archaeological discoveries, geological history, and contaminated groundwater or soil that needs to be cleaned up. Ecosystems can develop habitats in the subsurface. This new idea called geosystem services seeks to highlight the value of underground resources to people.

Increasing the capacity of public transportation south of the city center is the railway's main objective. These passageways, however, present various difficulties in terms of the geology, above- and below-ground conditions, and existing structures. The municipality will suggest fewer viable routes after the master plan becomes enforceable, based on a location analysis.

1.1.1 Aim and Objectives

The specific objectives of this study are:

1. To assess the current geosystem services within the tunnel corridor by utilizing map resources and databases.
2. To evaluate the present state of geosystem service utilization within the study area.
3. To examine the potential impact of construction proposed tunnel routes on the utilization of geosystem services, both presently and in the foreseeable future, through the application of GIS.

This study will evaluate the effects of three different tunnel pathways that have been suggested for Gothenburg's railway infrastructure on the environment, society, and the economy. By assessing the impacts on current geosystem services, and come up with the stretches with the least negative and most positive impacts in relation to effects on geosystem services.

1.1.2 Limitations

The list of geosystem services listed in Chapter 2, which are based on the report "To incorporate subsurface services in the planning" (Norrman et al., 2021b), serves as the basis for this study's examination. In the region of Gothenburg, these services are thought to be pertinent for subsurface planning. Chalmers created the SUB matrix in association with Luleå University and the City of Gothenburg (Norrman et al., 2021a). Depending on the geosystem service being researched, the study area is confined to a 100-meter-wide corridor along the possible tunnel, and the analysis is only done at ground level and the level at which the tunnel is expected to be built.

2

Theory

2.1 Geosystem Services as a Concept

The primary goal of the review on geosystem services by (Frisk et al., 2022) was to identify articles with precise definitions or examples of geosystem services. Emrik's review used as a general framework for understanding geosystem services. Later on using a SUB matrix categories as a specific framework originally based on subsurface qualities from flatosmotet report. Which explains the the idea of "geosystem services" and how crucial it is for using subsurface resources sustainably. It is said that subterranean development is prioritized first and is mostly unplanned these days. The need of recognizing the significance and application of geosystem services in society's planning and decision-making is underlined. Abiotic (eco)system services from the subsurface, such as groundwater ecosystem services, must be considered in planning, and the study outlines how to do so. It is recommended that more research be done on the idea of "geosystem services" and its applicability to planning. This research highlights the need of subsurface planning for smaller towns as well as larger cities, and the necessity of integrating subsurface features for a sustainable use of the subsurface. The geology of the region is examined, and current and prospective subsurface resources are mapped using classifications of attributes including supply, supporting, cultural, and regulating which is explained in later sections (Norrman et al., 2020). Evaluations of the extent of use and prospects for future application of the subterranean resources are also included in the research. In addition, the analysis analyzes the current land use in the area and outlines the potential effects of future plans on various subsurface resources. For Articles were deemed eligible if they met at least one of these requirements. The review concentrated on journal papers about geosystem services or abiotic services that were written and published in the literature about geoscience, geo conservation, or ecosystem services. Only peer-reviewed English-language articles met the inclusion requirements. Three crucial actions were part of the review process: The research field is mapped by 1) locating and compiling pertinent research, 2) objectively assessing research articles, and 3) combining the results into a coherent thesis regarding geosystem services. Following the initial stage of locating relevant articles, a review of the literature was conducted to find examples of geosystem services and classify them. The authors used examples from the literature or their own ideas in the absence of examples to determine the associated advantages of the geosystem services.

The concept of geosystem services is very crucial for the sustainable use of the subsurface. The subsurface refers to the region beneath the Earth's surface, encompassing both underground and underwater areas. On one hand, we can identify ecological systems, such as terrestrial biomass and marine ecosystems, which are influenced by factors like light, water, and oxygen availability, and involve various living communities and activities. On the other hand, the lithosphere and its geosystems have limited biological activity due to the absence of light and frequently anaerobic conditions. Geosystems are characterized by specific geological features, landscapes, rock types, minerals, and fossils. They are also affected by geophysical and geochemical factors, including the risk of natural disasters like earthquakes, landslides, liquefaction, and subsidence, as well as human activities like subsurface construction, mineral extraction, and pollution.

Achieving sustainable development in the subsurface requires understanding abiotic resources, including three-dimensional space, and recognizing their significance for human well-being. However, there's currently a lack of authoritative assessments regarding the role of the subsurface and its associated environmental trade-offs. This gap exists because of the absence of a comprehensive and integrated framework for addressing the subsurface and its contributions to human welfare (de Mulder et al., 2012).The utilization of the novel concept of geosystem services, which complements the concept of ecosystem services, is embraced. This new concept is introduced to enhance our understanding and evaluation of the services provided by geological and geospatial systems. , we not only gain a better foundation for comprehending the intricate interplay of natural and human-related processes within the subsurface but also establish stronger connections with a community of geoscientists and stakeholders who may not have been closely aligned with the well-established ecosystem services movement (Armstrong et al., 2012).

The geosystem services were divided into seven broader groupings with overlapping services after locating pertinent articles, such as Groundwater resources for drinking and Groundwater used as a material. These categories were listed as follows: A) Stable and safe environment; B) Groundwater; C) Underground space; D) Underground materials resources; E) Underground energy resources; F) Underground cultural heritage repository; and other (Gray, 2011). Thereafter, each group was independently searched using targeted keywords, followed by a generic search phrase associated with common economic valuation terminology and techniques.

Geosystem services encompass the benefits and contributions to human well-being that originate from the subsurface. The term "geosystem services" was introduced by in 2005 (Gray, 2005) during a discussion about the relevance of abiotic components in defining ecosystem services and preserving geodiversity, building upon his earlier work in 2004 and 2011 (Gray, 2011). The categorization of geosystem services aligns with the framework established by the Millennium Ecosystem Assessment (MEA).

2.1.1 Provisioning Services

This describes the tangible goods, materials, and products that ecosystems directly benefit humans with. The creation, acquisition, and distribution of natural resources—which are essential to both economic activity and human welfare—are included in these services (Highley & Bonel, 2004). The subsurface primarily serves as a source of essential materials and resources, which have been extracted for various purposes over millennia. Natural resource management places significant emphasis on the extraction of material resources from the subsurface. This becomes especially critical with the global population growth, where geosystem provisioning services, such as building materials, are increasingly valuable and, in some cases, scarce (Highley et al., 2004). Notably, the stocks and flows of rare earth materials have geopolitical significance, although such abiotic flows from construction and mining activities are often excluded from the conventional concept of ecosystem services. Following are some of these are : Geothermal Energy, Process water resources, Groundwater resources, Geomaterials and Minerals.

2.1.2 Cultural Services

The non-material advantages that ecosystems offer to people, such as recreational, spiritual, and cultural activities, are referred to as cultural services. These services improve communities' quality of life by supporting their cultural identity and general well-being. Following are some examples of this type. Archaeological Sites and Cultural Heritage: The subsoil is home to several archaeological sites and geological formations, as well as historic ruins. Due to their historical and cultural relevance, these locations draw tourists and encourage cultural tourism.

Geographical and Geological Features: Special geological features offer aesthetic and recreational value. Examples of these characteristics include rock formations, canyons, and caves. They promote a sense of pride and a connection to the place by frequently acting as monuments and symbols of regional or national identity. More than 10 percent of World Heritage sites feature earthen structures, which can enhance cultural prosperity. Examples include certain U.S. National Parks with cave systems (e.g., Mammoth Cave) and unique geological features such as the carboniferous rocks at the Heijmans quarry in the Netherlands or the cultural significance of locations like Ayers Rock for Indigenous people in Australia (UNESCO, 2015).

2.1.3 Regulating Services

These include the natural processes that support and uphold the functions and conditions of the environment. The resilience, stability, and usefulness of ecosystems as well as human activity are enhanced by these services. These services are increasingly harnessed in energy systems, such as heat-cold storage systems that utilize the subsurface's ability to regulate temperatures. The presence of permafrost and its potential responses to climate change are noteworthy examples that could impact subsurface regulating services. Systems in Sweden that extract and redistribute heat and cold stored underground rely on this regulating function of the subsurface, rather than geothermal heat derived from deeper earth processes. Thawing permafrost can impact existing infrastructure, leading to stability issues and environmental risks. On a broader scale, long-term geochemical cycles within the geosystem play a vital role, including carbon sequestration and the implications of carbon capture and storage (CCS) as a technology for mitigating climate change. Following are some examples of this category: Geo Energy, Clean and safe soil, Water retention in soils and rock, water filtration capacity (Dahl & Stedman, 2013).

2.1.4 Supporting Services

While not separately identified in the CICES framework (Common International Classification of Ecosystem Services), supporting services from the subsurface are essential. They create a stable environment for construction and habitation. The urban growth and increasing resource demands underline the growing importance of geosystem services concerning subsurface use and the impacts of human activities on current and future uses. These supporting services involve utilizing underground spaces for living, tunnels, and infrastructure for public services. Additionally, they encompass addressing potential hazards, both natural and human-induced, from the subsurface, such as earthquake risks. De Groot (2006) (Groot, 2006) distinguished the carrier function, which could be labeled as carrier services, emphasizing the vital role played by the subsurface in providing a stable platform for various activities.

2.2 Supporting Geosystem Services

2.2.1 Bearing Capacity and Soil Stability

One of the most important parts in the construction of any structure is to have a well and calculated knowledge of the stability of soil and its capacity to bear the weight of the structure, i.e., bearing capacity. Different types of soils and rocks exist in the world, having different properties and they show different types of behaviors towards construction whether above or below the ground surface. Clay and rocks are examples of two different types of material. The soil-type clay is very soft and is a very unstable material as compared to the rock, e.g., Schist, which is very hard and considered a very stable rock type. In Sweden, there are rocks having high zones of fracturing and due to this, they show high deformations (Allen, 2002). Such behaviors cause an impact on the bearing capacity of the soil on which structures are to be made. For the safe construction of tunnels, buildings, dams, and roads, the bearing capacity and stability of soil are very highly significant.

2.2.2 Space for Horizontal and Vertical Constructions

There are two types of underground infrastructure constructions, i.e., horizontal and vertical constructions. Vertical constructions that can be constructed below the surface level include buildings, garages, storage tanks, etc. They are very useful in forming a secure environment and maximizing the space on the ground surface

(Taromi Sandström et al., 2021). These constructions can also help in storing dangerous materials, and thus their depth can be decided according to the nature of the material.

Similarly, horizontal structures are constructed underground the surface, such as tunnels, audits, subways, etc. The purpose of having horizontal constructions is to lower the transit time, and people can reach their destination on time without any traffic blockages. Such constructions also provide a safe passage with a clean and secure environment (Zargarian et al., 2016). Nowadays, it has become a new fashion to build underground infrastructures.

2.2.3 Space for Cables and Pipes

During underground construction, there are some wires, pipes, and cables. Wires, pipes, and cables are used for providing electricity, water, and sewage through pipes for the infrastructures. These things were generally placed below the ground surface because they occupy massive space and cause trouble for the public above ground (Kuchler et al., 2024). Cables, wires, and pipes are often placed below the Earth's surface commonly 2-6 meters below so that structures could have easy access to them for the facilities they provide (Noon, 1997). Moreover, wires, cables, and pipes below the surface of the Earth are very secure and they are protected during war or any bomb attacks on the surface.

2.2.4 Underground Storage

Another important structural feature that can be found underground is the storage places. These storage areas/cavities can be either for water storage purposes or for storing different types of gases, e.g., carbon dioxide or natural gases. These tanks can help collect rainwater so that it can further be used for various commercial as well as domestic purposes. Underground storages were usually built on rocks having high porosity and permeability so that the Earth's surface could capture the gases and water and store it (Taromi Sandström et al., 2021). The most common types of rocks that can be utilized for underground storage are sedimentary rocks, because of their porous and permeable nature (Kuchler et al., 2024).

2.3 Cultural Geosystem Services

2.3.1 Known and Unknown Heritage

Before starting any underground construction in the cities' area, there are historical sites that can be termed to be known and unknown heritage sites. Known heritages are those historical sites that are discovered and preserved by the archaeological department to signify the cultural importance to the people, while unknown heritage sites are those sites that have not been investigated archaeologically yet but can be labeled as cultural heritage in the future (Henderson, 2019) (Körner & Wahlgren, 2015). It is a very complicated task to build underground structures having these heritages as they are protected by the laws of the country. Permission must be taken from the relevant authorities to construct the structure under such sites because of the danger of collapsing during construction beneath them.

2.3.2 Geological Heritage

Geological heritage also plays an important role and should be taken under serious consideration during underground construction. It deals with the past of Earth's making and the habitat that lived millions and billions of years ago. It can be further classified into extremely important geological formations such as older rocks having wide information about geology and geological features (Körner & Wahlgren, 2015). It should be taken under serious care as it gives major resources for different types of species (Gray, 2011). So during the planning phase of any construction, the geological heritage land must be considered so that it cannot be exploited because of being a rare resource. These geological heritages can also be termed as Geodiversity and Geotope.

2.4 Regulating Geosystem Services

2.4.1 Geoenergy

Geoenergy is an example of utilizing the underground energy trapped in between the rocks, groundwater, and soils when the sunlight causes the ground to be heated up. This geoenergy is present at shallow depth. Shallow geothermal systems use the relatively constant temperature of the ground just a few meters below the surface to provide heating and cooling for buildings. This underground energy due to sunlight can be used for different purposes, including the major one for electricity purposes. There are many sources in which Geoenergy can be stored like groundwater heat, etc. Geoenergy itself can be used for the storage of heat and energy directly from the sun (Taromi Sandström et al., 2021). There are many Geoenergy facilities, approximately in millions, installed in Sweden as they are eco-friendly and provide an alternative for other heating devices.

2.4.2 Clean and Safe Soil

Clean and safe soil is also an important part of construction on underground surfaces. Ground that is polluted with human or industrial waste is dangerous and risky for underground construction as it poses serious health and life threats to the people (P. Andersson, 2022). This pollution can be due to the human activities and industrial waste that can be dumped into the water which seeps into the soil while some of the waste that pollutes the soil is the medical waste from the hospital and the explosives that were left unchecked on the ground which later goes into the soil and pollutes it. In this way, the soil under the Earth's surface becomes toxic and becomes a serious threat for constructing in such ground. For the safe construction of underground structures, it is a must to evaluate the soils in which structures are to be made so that they will be safe and clean for the people who go on a routine basis (SPIMFAB, 2014).

2.4.3 Water Retention in Soil and Rock

Soils and rocks have a very unique property of water retention. The intensity of water retention depends upon the nature of soils and rocks and their properties like porosity, permeability and retention against water. In order to retain the water, the material of soil must be capable of storing water either through storage tanks or groundwater formation (Bartel, 2016). Materials having excellent water retention properties can help in reducing the effect of flooding. Water retention can be lower when there are large holes and cracks in the rocky formation and also have less intensity of precipitation which causes infiltration in the materials. Geomaterials are also considered to have poor water retaining capacities due to continuous weathering and erosion (Stråhle, 2001).

2.4.4 Water Filtration Capacity

Water filtration is also a property that can be exhibited during the construction of any underground structure. The material in which the construction is going to be done must be able to infiltrate the water. This can help in infiltrating the water and make it cleaner by removing the impurities (P. Andersson, 2022). This water can then be used for drinking purposes for people. During any construction, there will be a layer for waterproofing that can be installed which can lower the capacity of infiltration, thus causing a lessening of filtering capacity.

2.5 Provisioning Geosystem Services

2.5.1 Geothermal Energy

Geothermal energy is a renewable form of energy that is derived from the heat that is naturally produced within the Earth's crust. This heat is generated by the decay of radioactive isotopes, as well as residual heat from the formation of the planet (Geological Survey of Sweden, 2022b). Geothermal energy can be harnessed for a variety of applications, including electricity generation, space heating, and cooling. There are two main types of geothermal systems used in Sweden: shallow and deep geothermal systems. Deep geothermal systems, on the other hand, use the high temperature of the Earth's crust several kilometers below the surface to generate electricity (Li et al., 2015).

2.5.2 Drinking and Process Water Resource

For drinking and cleaning purposes, it must be necessary to store the water either on the surface or below the surface of the Earth. The water is usually stored in between the cracks and pores of soils and rocks. Sedimentary rocks are excellent for storing water because of their porous and permeable behavior while glacial sediments are the best example in the case of soils (Geological Survey of Sweden, 2021a, 2022c). Crystalline rocks can also be able to store the groundwater but they are not as good as that of other sedimentary rocks. A high amount of salt and iron can impure the soil and decrease the quality of groundwater.

2.5.3 Groundwater Resource

During the construction, it is necessary to maintain the groundwater resource. Groundwater is an important resource not only for drinking purposes but also to stabilize the environment and ecosystem for animals, plants, and humans. Increasing and decreasing groundwater levels cause different types of problems on the surface (Gray, 2011). For example, an increase in the groundwater level causes floods and landslides while a lowering in the groundwater level causes the plants to decay because of the low water level. An increase in the pore pressure leads to low slope stability. Observing all the factors, if an underground tunnel is going to be constructed, it must be ensured that it will be fully tight and make no new pathways for the water to drain so that groundwater level should be maintained (Hjerne, 2021). Changes in groundwater levels can influence the stability of the surrounding soil and rock layers. A sudden drop in groundwater levels may lead to subsidence, which can damage surface structures and infrastructure. Alterations in groundwater levels can affect ecosystems dependent on groundwater, such as wetlands or vegetation. Fluctuations may harm aquatic life and impact the balance of local ecosystems. For tunneling projects, maintaining groundwater levels at a consistent level is crucial to ensure the stability of the tunnel and prevent water infiltration into the tunnel, which can lead to maintenance issues (Hjerne, 2021).

2.5.4 Geomaterials and Minerals

During the construction below the surface of the Earth, there are many different types of geomaterials and minerals encountered in the ground. These geomaterials and minerals are sometimes very rare and need to be protected and must be extracted according to the laws of that country. These geomaterials include soils, sands, gravels, minerals, and rocks. These materials are used for the infilling of the foundation along with various other purposes for stabilizing the ground surface (Geological Survey of Sweden, 2022a) (B. Andersson, 2022). The extraction of these materials and minerals must be done in accordance with laws, and special permits must be taken to build any structure along these sites. Tunnel construction and shaft making are examples of the structures that cause serious concerns to these materials as the construction of these structures requires drilling and blasting which causes major damage to the Earth's surface so they must abide by the rules and laws of extraction of geomaterials and minerals from the soil of that areas (Allen, 2002). Minerals, on the other hand, are formed by different geological processes and contain a special physical and chemical composition. They are usually very rare and have a significant importance in daily life. So, there is no construction allowed to be done at those sites having geomaterials and minerals of high importance according to the environmental codes.

3

Methodology

The possible effects of tunnel construction on subsurface ecosystems in three separate corridors are assessed using a multi-criteria analysis as a technique approach. The investigation took into account which include economic, social, and environmental factors (Sutcliffe et al., 2021).

In order to accomplish this, the study will look into the current land use and existing geosystem services along the corridors for the proposed tunnels, assess the viability of utilizing the geosystem services already present in the study areas, define the environmental, social, and economic aspects of those services, and assess the effects of tunnel construction using multi-criteria analysis.

Establishing a precise definition of the issue or choice that must be decided is the first stage in conducting an MCA (Belton & Stewart, 2002). This includes deciding on the objectives and criteria that will be applied to the evaluation of the options. The criteria are created and defined next. These standards must be relevant, quantifiable, and directly tied to the decision-making issue. Also, each criterion should have a distinct weight or level of importance assigned to it, and they should be independent of one another (Taha, 2007). Finding the options that will be assessed is the third phase. These options should illustrate the various approaches that can be taken to solve the choice problem, and they should be practical and realistic (Zaraté et al., 2021).

For every option and standard, data is gathered. This can involve gathering primary data through surveys or interviews or secondary data from published reports or databases. Many techniques are used to examine the data, including pairwise comparisons, decision trees, and weighted scoring. By comparing each choice to one another and identifying their advantages and disadvantages, this analysis can aid. Based on the criteria and objectives, the analysis's findings are presented together with a recommendation for the most appropriate action. A description of the analysis's limitations and recommendations for further study should be included in the conclusions (Wang et al., 2022).

3.1 Multi-criteria analysis as a method of assessment

MCA is a helpful tool for making decisions because it can assess several options according to different standards. Setting goals and determining pertinent assessment elements are the steps in the process that determine how well each alternative satisfies the goals (Lootsma, 1997). The criteria that will be taken into consideration are first defined by the decision makers and might be either quantitative or qualitative in nature. Aspects that are social, technical, environmental, and economic are some examples (Belton & Stewart, 2002). The performance of several options in relation to each criterion is then recorded. Each alternative's overall value is determined by MCA using weighted scores. The procedure makes it possible to visualize option trade-offs (Belton & Stewart, 2002). MCA has become more and more popular when it comes to public sector investment decisions that need to balance a lot of intricate aspects.

The decision problem is precisely defined at the outset of the MCA process, and a collection of viable options or solutions is produced (Belton & Stewart, 2002). The performance of each alternative is then evaluated by identifying pertinent assessment criteria (Wallenius et al., 2008). Environmental, social, economic, and aspects may be included in these requirements. The degree to which each option meets each specific condition is then measured. The relative importance of each criteria to the stakeholders determines how heavy it is. MCA then uses mathematical methods like weighted summing or outranking to determine an overall score for each solution (Ishizaka & Labib, 2011). This makes it possible to compare alternatives directly even when they are measured on various scales.

In this research, each tunnel route is analyzed for different geosystem services, keeping in view the subsurface factors. Every tunnel route is analyzed by overlay analysis of multiple layers of factors and each factors contribution is observed. Each factor is given an impact rate based on its importance. This overlay analysis is performed in GIS Software. Then further the social, environmental and economic impact is analyzed for each route. MCA table is designed on the basis of good,neutral and bad impact of tunnel routes on geosystem services. MCA was used to analyze each tunnel routes on the basis of number of factors in the context of following effects:

Social Impact: Geosystems can pose significant safety and risk challenges in tunneling. Using MCA, the consideration of various safety criteria, such as risk of collapses, groundwater infiltration, lowering of groundwater levels, damage to national heritages was made. By assessing these risks alongside other project goals, during construction informed decisions can be made to enhance safety measures.

Environmental Impact: Tunneling projects can have a substantial environmental footprint. Using MCA, the environmental impact of tunnel construction in terms of factors like habitat disruption, pollution, and noise was also assessed. By considering these factors alongside social and economic criteria, a balance between project goals and environmental sustainability was considered.

Economic Impact: The economic aspect is crucial in tunneling. MCA is used to evaluate the cost-effectiveness of different geosystems and what effect does the tunneling cause due to change in the present geosystem. For example, in terms of bearing capacity, the MCA was helpful to chose the path where least reinforcement and lining is required to keep the project economical. By quantifying and comparing costs and benefits, decisions that optimize the return on investment could be made.

The methodology applied in this research was a multicriteria analysis to evaluate each proposed tunnel corridor. The potential effects of each corridor were assessed on the basis of the following scales:

Negligible: No known effect anticipated.
Minor: Small change from current conditions anticipated.
Moderate: evident change from current conditions anticipated.
Major: Large change from current conditions anticipated.

This evaluation was conducted using a "do nothing" concept, which considered what effects tunnel construction would have on geosystems if no mitigation or management measures were implemented. Potential impacts were identified by analyzing how geosystem services may fluctuate or be influenced from baseline conditions with the introduction of each tunnel corridor option.

3.1.1 GS Categories and Data Collection

The idea of geosystem services offers a framework that is both appealing and difficult. On the one hand, it acts as a thorough description and classification of the advantages humans derive from abiotic resources in the subsurface, highlighting resources that could otherwise go unreported and promoting interaction between professionals and laypeople. Yet, it oversimplifies a complicated and interdependent world. The literature research on geosystem services also shows that the definition of the term changes depending on the readership and goal of the authors.

The geological systems beneath the surface of the earth provide several crucial functions to people and society. Hence, the subsurface is a resource with several uses that offer so-called geosystem services. Undefined as of yet, geosystem services refer to the benefits that the earth's geological system provides to humans in terms of well-being and quality of life (Gray, 2011). Four categories of geosystem services are distinguished: supporting, cultural, regulating, and provisioning. The study "Integrating subsurface services into planning" served as the basis for the list of geosystem services mentioned in this chapter (Norrman et al., 2021b).

The information used to create the map materials is sourced from publicly available data provided by various organizations, including the Geological Survey of Sweden, the Land Survey, the County Administrative Board, and the Riksantikvarieämbetet. Additionally, data from the City Planning Office in Gothenburg is included and detailed in Table 3.1.

Table 3.1: Geosystem Services Data Sources

Geosystem Services		Data Source
SUPPORTING SERVICES	Bearing Capacity	• Assessment based on maps with bedrock and soil types obtained from SGU's open data (source)
	Space for sewerage, cables and utility lines	• Data sourced by (source)
	Space for underground Construction	• No Data
	Space for Underground disposal and storage	• SGU's open data source (source)
PROVISIONING SERVICES	Groundwater resources for drinking and as a material (industrial and irrigation purposes)	• Assessment based on maps with bedrock and soil types obtained from SGU's open data (source)
	Extraction of geomaterials	• Soiltype and Bedrock map data obtained from SGU's open data source
	Fossil energy resources	• No Data
	Geothermal resources	• No Data
REGULATING SERVICES	Regulation of erosion	• Assessment based on maps with bedrock and soil types obtained from SGU's open data (source)
	Regulation of groundwater quantity and quality	• Assessment made on the basis Hydrological data, Soil type and bedrock maps obtained from SGU's open data source (source)

Geosystem Services (Continued)		Data Source
	Regulation of temperature by underground thermal storage capacity	• Assessment made through Uranium Map and Geoenergy well data obtained from SGU's open data source (source)
	Regulation of soil and bedrock chemistry, including contamination potential	• Uranium content map obtained from SGU's open data (source) • Potentially contaminated areas obtained from the County Administrative Board's open data (source) • Radon risk map data is unavailable however assessment is made using a literature review
CULTURAL SERVICES	Historical, recreational and sacred sites	• Assessment based on maps with bedrock and soil types obtained from SGU's open data (source)
	Geological Heritage	• SGU's open data source (source)

3.1.2 Evaluation and Conflict Analysis of Geosystem Services using GIS

The evaluation of the feasibility of utilizing geosystem services and identifying potential conflicts related to these services is conducted through custom Geographic Information System (GIS) maps. These GIS maps are specifically created for geosystem services that exhibit varying requirements along the route or may be influenced by the construction of a potential tunnel. This assessment employs a color-coded system, which is documented in Table 3.2. The color coding used is tailored to the specific site being investigated.

Table 3.2: Assesment based on Geographic Information System (GIS) maps

	Geosystem Services	Label Colors	Description
		● Poor Bearing Capacity	• The soil is mostly clay

	Geosystem Services	Label Colors	Description
Supporting	**Bearing Capacity**	🟡 Moderate Bearing Capacity 🟢 Good Bearing Capacity	• Stable bedrock with fractured zones • Bedrock with good load bearing capacity
Cultural Services	**Geological Heritage**	🔴 Geological Heritage 🟡 Geological Heritage 🟢 Geological Heritage	• Geological heritage within tunnel section • Geological heritage near tunnel section • No Geological Heritage
Provisioning	**Groundwater Quality and Quantity**	🔴 Very Unstable Levels 🟡 Unstable Levels 🟢 Stable Levels	• Measured levels are unstable and below normal over a certain period • Measured groundwater levels are below normal above a certain period of time • Measured groundwater levels are stable up to a certain period of time
	Geothermal Resources	🔴 Very Unstable Levels 🟡 Moderate Potential 🟢 Good Potential	• Measured levels are unstable and below normal over a certain period • There are extensive clay layers that exist between the bedrock and the ground surface. • There are substantial clay layers that extend relatively deep between the bedrock and the surface of the ground.

	Geosystem Services	Label Colors	Description
Provisioning		● No Potential	• It is situated near the bedrock with minimal presence of deep clay layers or obstructions. The tunnel is positioned between the ground surface and is at a depth suitable for accommodating energy wells.
Regulating	**Clean and Safe Soil**	● High Risk	• Elevated levels of both radon and uranium, or the presence of activities such as gas stations that have the potential to contaminate areas.
		● Moderate Risk	• There are moderate levels of uranium or areas that may potentially be contaminated.
		● Low Risk	• There are no recorded elevated levels of uranium, and there are no areas that are potentially contaminated.

4
Case Study

The case study focuses on a specific tunnel section as part of a potential railway project between Järnbrott and Änggården. Figure 4.1 (Berndtsson & He, 2022) illustrates various potential routes and represents the area of study. The study area is situated in Gothenburg and extends from Radiovägen in the south to Änggården in the north. The land use within the survey area primarily consists of residential areas, although industrial areas and forests are also present along the corridor. The southern part of the area is characterized by extensive forest coverage, followed by the presence of a preschool and Flatåsskolan after Marconigatan (City of Gothenburg, 2022a). Apart from these, the corridor mainly comprises residential areas. It is well observed in the Landuse map attached below (Figure 4.6) (Eriksson, 2015).

Figure 4.2, 4.3, 4.4 shows the elevation profile of all three tunnel routes. The use of elevation profiles in tunnel construction provides critical information for alignment selection, tunnel depth determination, groundwater management, vertical clearance assessment, and ongoing monitoring. By considering the existing ground elevation and potential variations, designers can determine the minimum height required for the tunnel to accommodate vehicles, equipment, and any overhead infrastructure such as utilities or rail lines.

The geosystems are assessed at the surface and at the depth where tunnels will be constructed. The soil types found in the Gothenburg area have primarily developed during the Quaternary period, which commenced around 2.5 million years ago and continues to the present day (City of Gothenburg, 2022b). The majority of these soils were formed during and after the last ice age, which started approximately 115,000 years ago and concluded around 10,000 years ago when Sweden became largely devoid of ice. During the ice age, the region was blanketed by a thick ice sheet that exerted immense pressure on the land, resulting in subsidence of the ground level (Allen, 2002). As the ice melted, a process of land uplift commenced, with the area experiencing a rise of about 2-3 mm per year. Soil type is a crucial factor to consider in tunnel excavation due to its impact on the stability and safety of the tunneling process. Different soil types possess varying properties that can influence excavation techniques, support systems, and overall tunnel design.

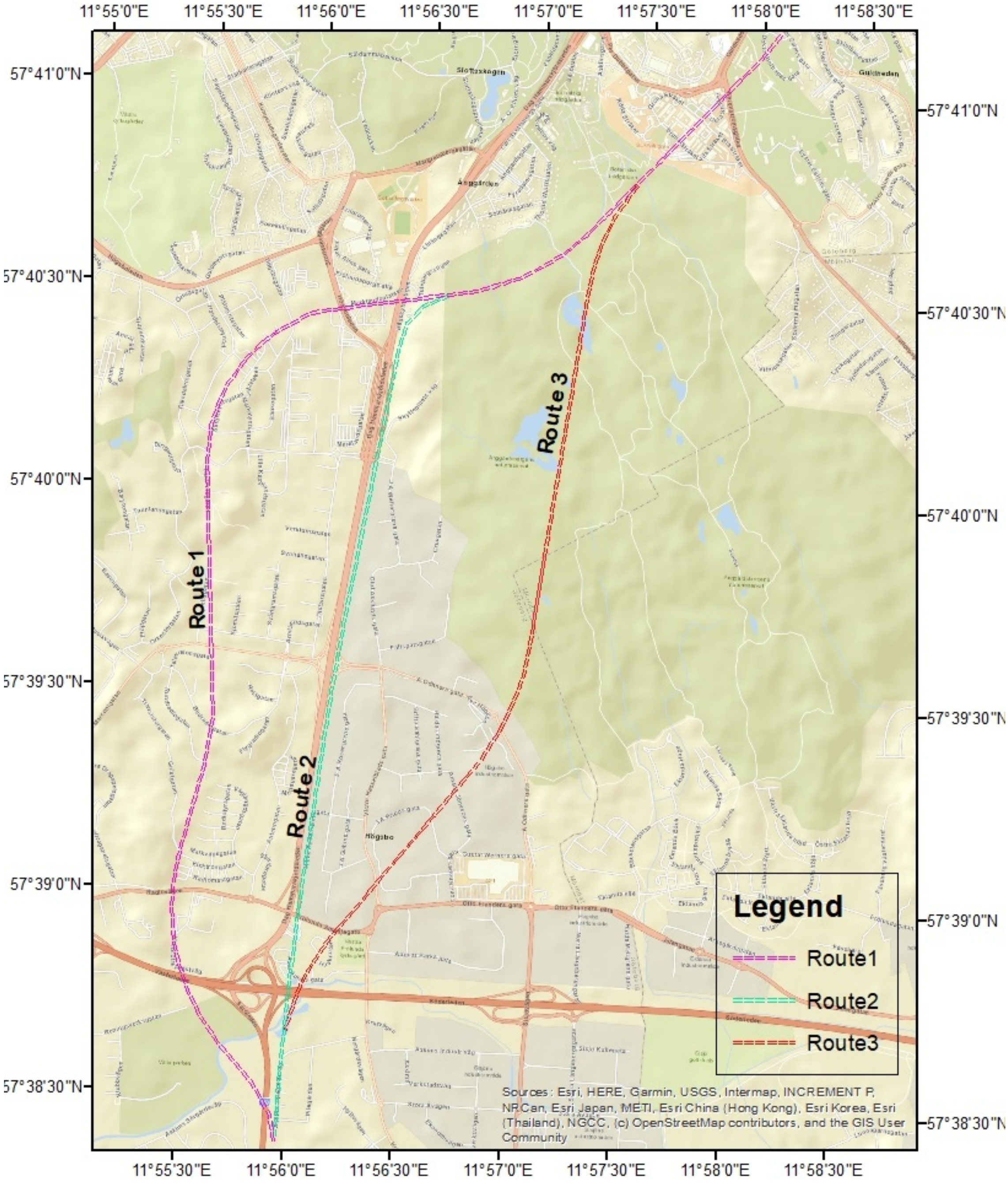


Figure 4.1: GIS based map of three possible railway routes. Stretches are included in the city of Gothenburg's plan

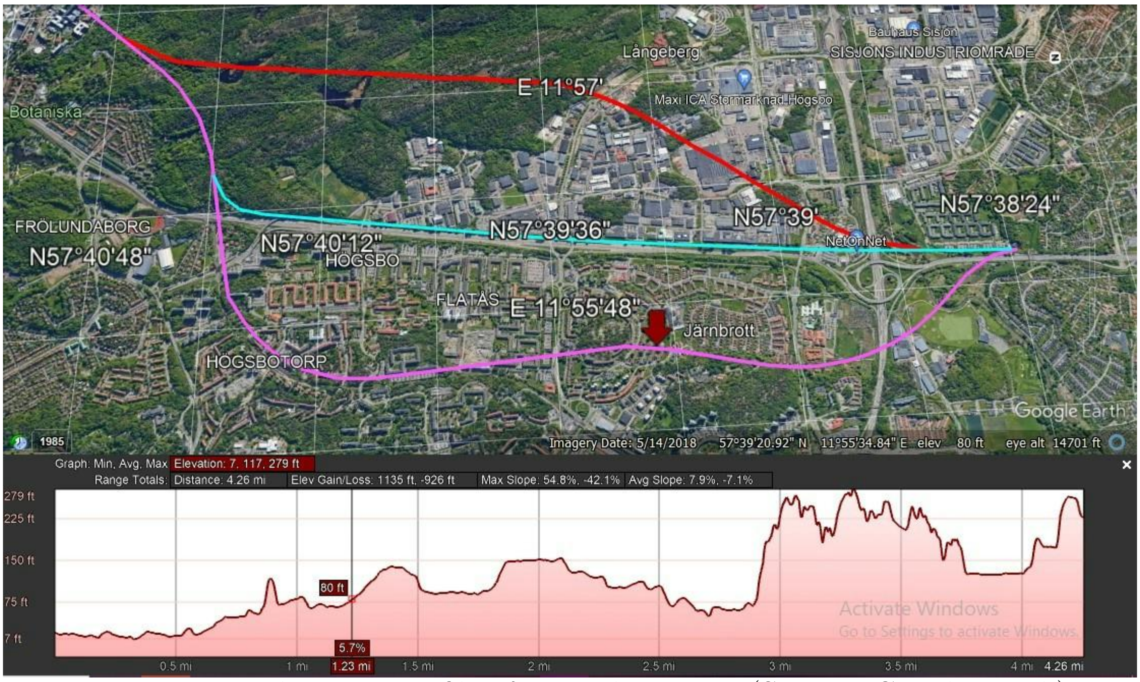


Figure 4.2: Elevation profile of Tunnel Route 1 (Source: Google Earth)

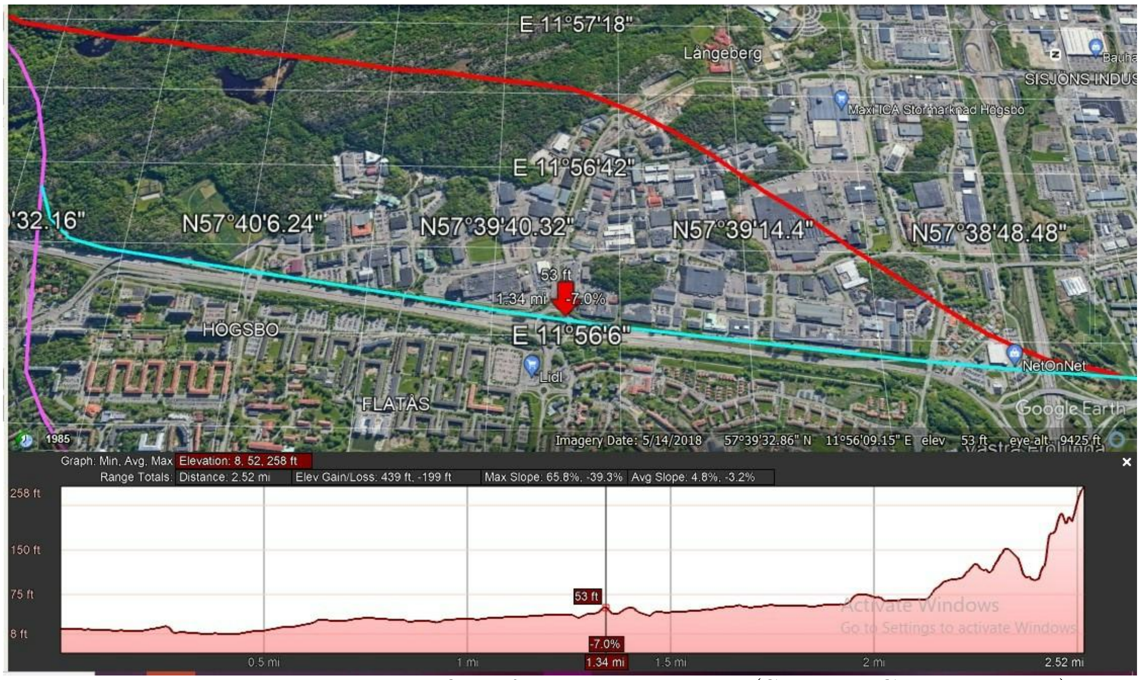


Figure 4.3: Elevation Profile of Tunnel Route 2 (Source: Google Earth)

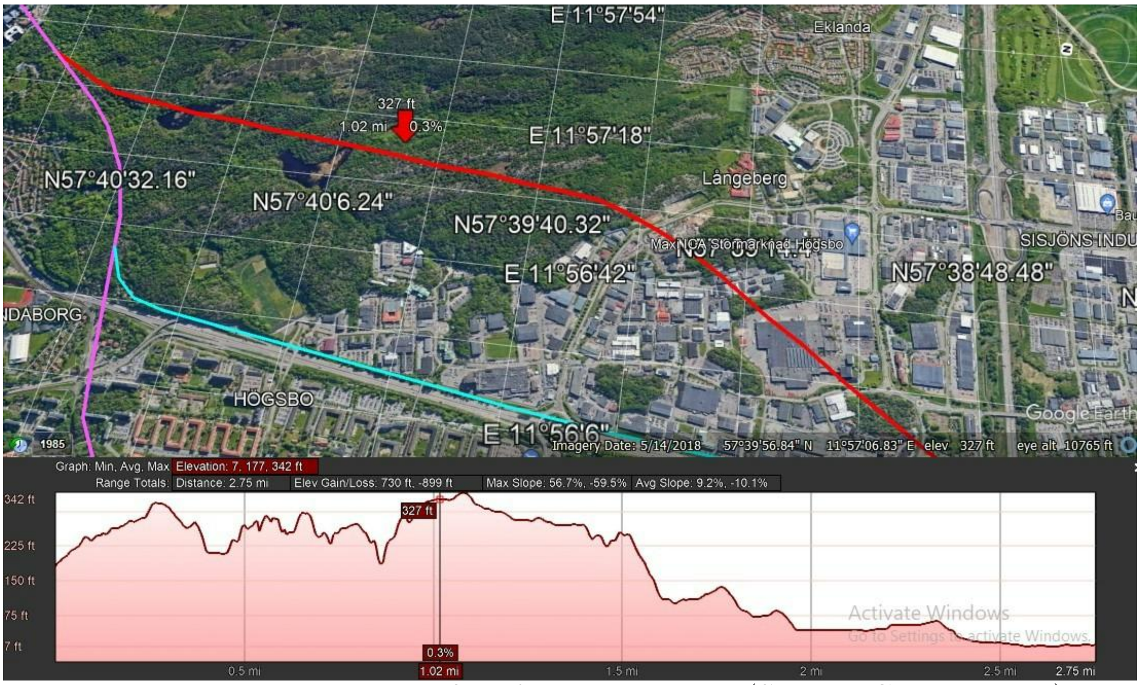


Figure 4.4: Elevation Profile of Tunnel Route 3(Source: Google Earth)

Based on Figure 4.5 (Geological Survey of Sweden, 2022e), the map depicts that soils in the coastal areas of Gothenburg are often influenced by marine deposits, with sandy and silty soils being common. These soils are relatively well-drained and are suitable for agriculture and horticulture. The archipelago and coastal zones also feature rocky outcrops and shallow soils, which provide a unique habitat for specialized flora and fauna. Moving inland, the soils are influenced by glacial activity and the subsequent land uplift. Glacial till, a mixture of clay, silt, sand, and gravel, is a prevalent soil type in the area. Glacial till soils can vary in texture, drainage, and fertility, depending on the composition and sorting of the sediment deposited by the retreating glaciers.

Along river valleys, alluvial soils are found, which are formed by the deposition of sediment carried by rivers. These soils tend to be fertile and well-drained, making them suitable for agriculture. Furthermore, the presence of moraines, which are accumulations of glacial debris, contributes to the soil diversity in Gothenburg. Moraine soils can range from sandy and gravely to clay-rich, and their characteristics depend on the composition of the underlying glacial material (Knappett & Craig, 2019).

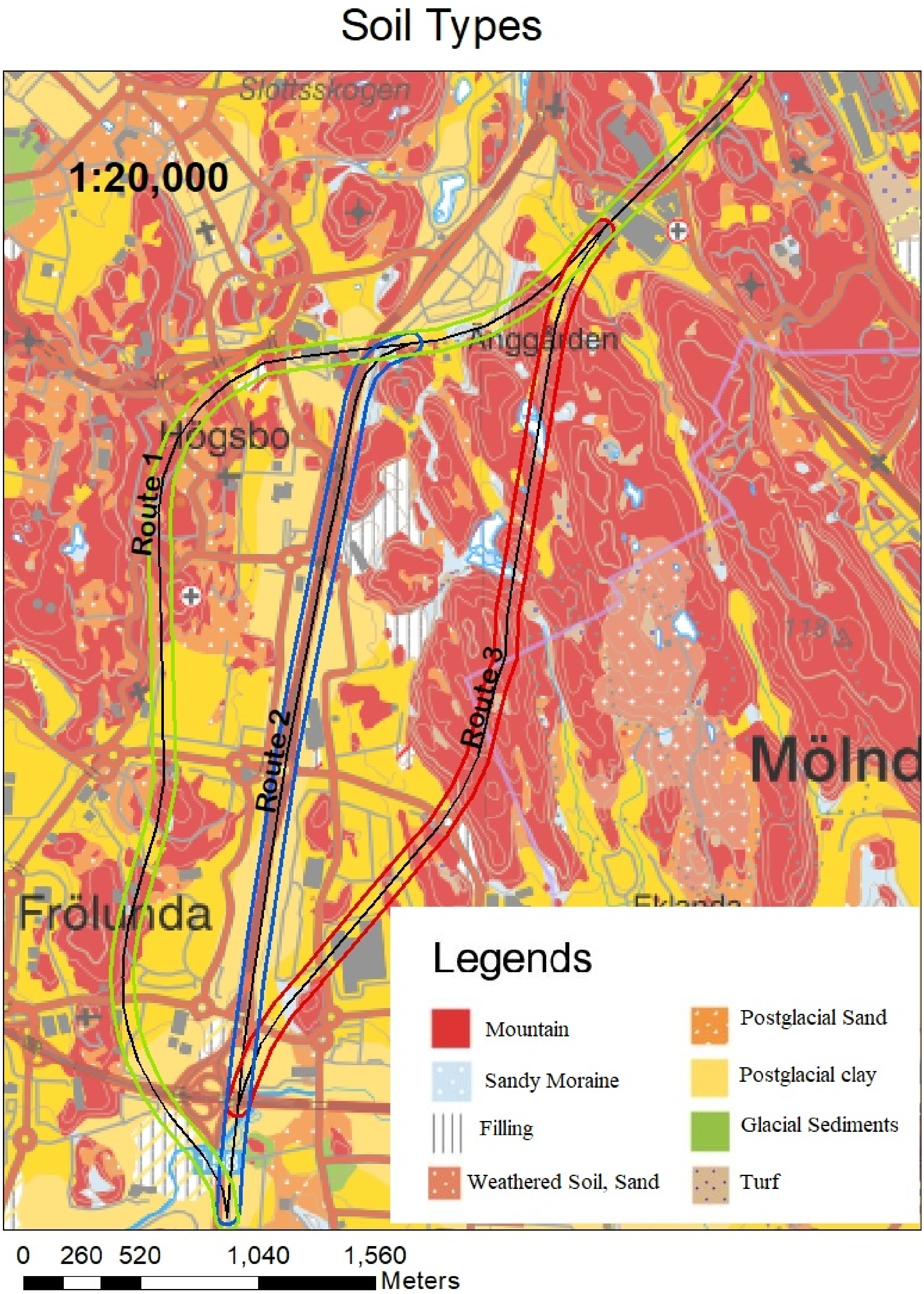


Figure 4.5: GIS Map of surface soil types along the possible tunnel routes

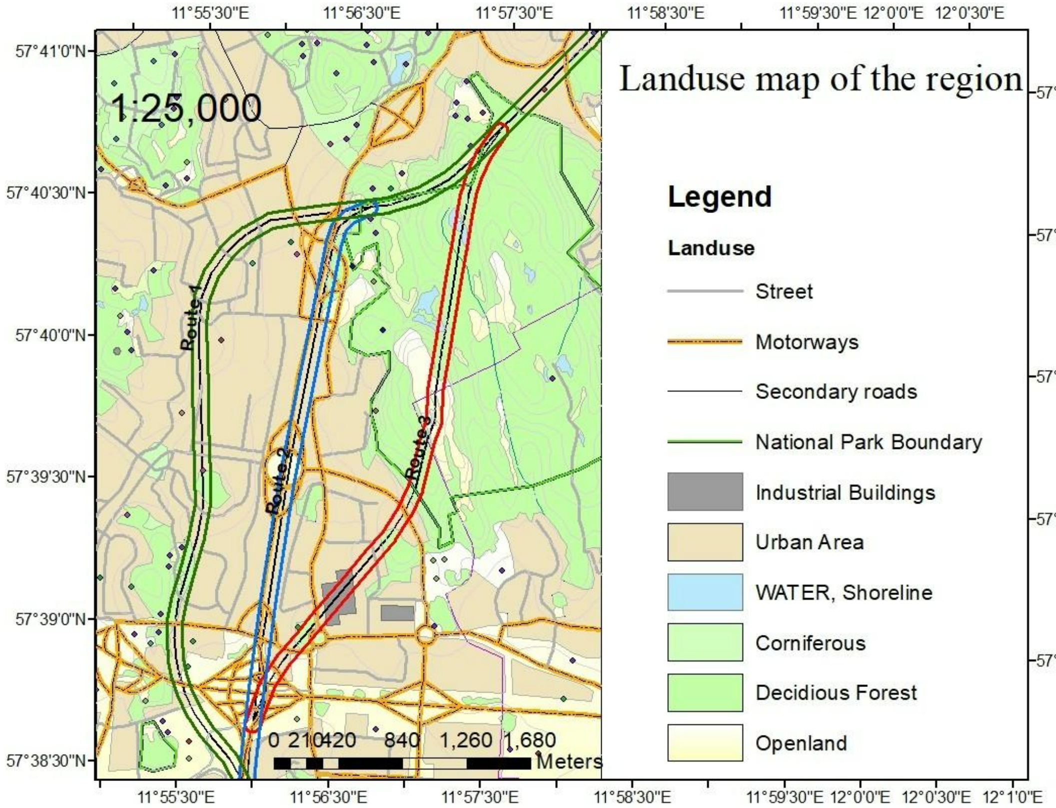


Figure 4.6: Land use Map of the Study Area

5

Results

The collection of map data followed in order to visualize the potential of different geosystem services within the tunnel corridor using GIS technology. Subsequent analyses were conducted to assess potential conflicts and synergies among the geosystem services, with consideration given to the possible construction of the tunnel. Additionally, evaluations were carried out to determine the potential impact of the tunnel on the geosystem services.

5.1 Supporting Geosystem Services

5.1.1 Bedrock and Structure

The soil is present at shallow depths except for tunnel route 2. (Figure 5.14.5). Specifically, the bedrock along the tunnel stretch comprises tonalite-granodiorite and granodiorite-granite. These rocks contain various minerals, including quartz, plagioclase, and potassium feldspar. The rock material presents an opportunity for valuable resource utilization. However, there is no national interest in extracting minerals from the area (Geological Survey of Sweden, 2021b).

The quality of the rock varies slightly, but it is generally suitable for use in road construction (quality class 2), as well as for railway and concrete applications (quality classes 1) (Eriksson, 2015). This means that the excavated rock material from the potential tunnel construction could potentially be utilized for these purposes.

Bedrock and structural maps help in identifying favorable routes for the tunnel alignment. By analyzing the geological features, such as faults, fractures, and rock types, engineers can select the most suitable path that offers stability and minimizes potential hazards. Bedrock and structural maps provide insights into the hydrogeological conditions and potential water inflows within the rock mass. This information assists in designing effective dewatering systems, drainage channels, and waterproofing measures to mitigate water-related risks.

Rock formations with high levels of faulting, squeezing ground, or potential for rockbursts can pose significant challenges during excavation and may require specialized engineering techniques and support systems. Identifying potential geotechnical hazards associated with different rock types is crucial for minimizing risks during tunnel construction. Based on Figure 4.4, tunnel route 1 cuts a plastic shear zone perpendicularly which means the tunnel requires proper reinforcement measures, such as rock bolts, shotcrete, or steel ribs, to ensure the stability and safety of the tunnel (Bartel, 2016). Tunnel route 2 and 3 contains brittle deformation zone which is a possible risk of rockfall hazard during excavation.Rockfall hazard is a big risk if it happens during tunnel construction. This proactive approach helps in developing strategies to minimize risks and implement appropriate mitigation measures during tunnel excavation.

The tunnel routes pass through igneous rock formations. Granite and Tonalite-granodiorite are considered competent rocks suitable for tunnel excavation in stable conditions. They offer good strength and integrity, which contribute to stable tunnel walls and reduce the need for extensive support systems. However, as with any rock type, the specific characteristics of the tonalite or granodiorite deposit, such as jointing, fracture patterns, and potential weaknesses, should be thoroughly evaluated.

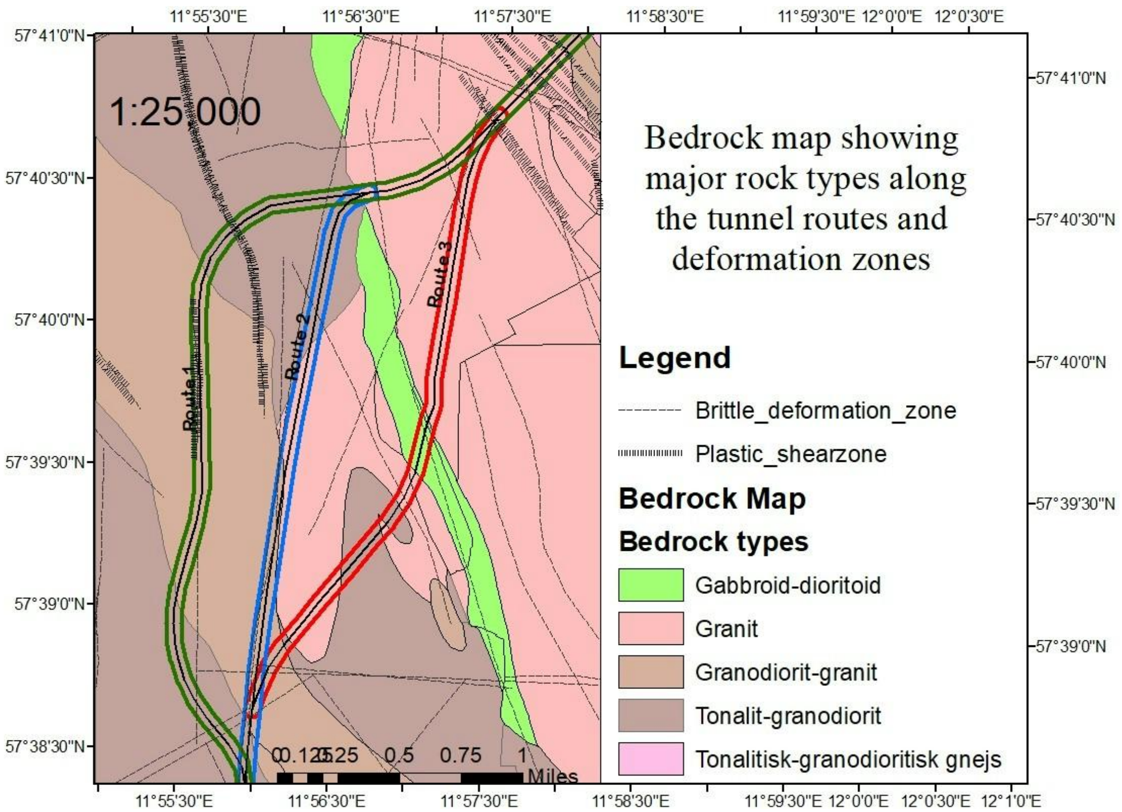


Figure 5.1: Map of bedrock along the possible tunnel stretches

5.1.2 Soil Depth and Bearing Capacity

The soil in the area generally exhibits good bearing capacity and long-term stability, while the potential for underground storage is limited. The rock formations consist of diverse granites such as tonalite-granodiorite and granodiorite-granite, which are stable and possess favorable bearing capacity.

Along tunnel route 1, three deformation zones are observed: one exhibiting brittle deformation, and the other two displaying plastic deformation. In the brittle deformation zones, cracks and fracture zones are present in the rock, whereas the plastic deformation zones contain features like shear zones, folds, and veins (Stråhle, 2001). Additional reinforcement of the rock may be necessary in the deformation zones located in the middle and northern parts of the stretch. The surface materials along the tunnel alignment primarily consist of post-glacial clay, glacial clay, and ancient rock.

As depicted in Figure 5.1 (Eriksson, 2015), all three route traverses mountainous terrain with a relatively good bearing capacity. The bearing capacity is not significantly influenced by other geosystem services, although it is comparatively weaker in areas with fracture zones. Consequently, extra reinforcement might be required in the tunnel sections passing through these fracture zones due to their lower bearing capacity. Bearing capacity also depends on soil depth and soil types. Glacial clay have lower bearing capacities and are problematic due to their swelling properties. Based on Figure 4.5, 5.1, 5.2 (Geological Survey of Sweden, 2021d), and 5.3. The red zones are the sections with poor bearing capacity which are very small sections. Overall all three proposed routes are considered good in terms of bearing capacity due to the large spread of bedrock at the surface level however at entry points, there is high reinforcement cost at tunnel section 1 and 2 as compared to tunnel section 3. Tunnel section 3 has bedrock at surface so no tunnel lining will be required for shaft and tunnel opening (Fig. 4.5).

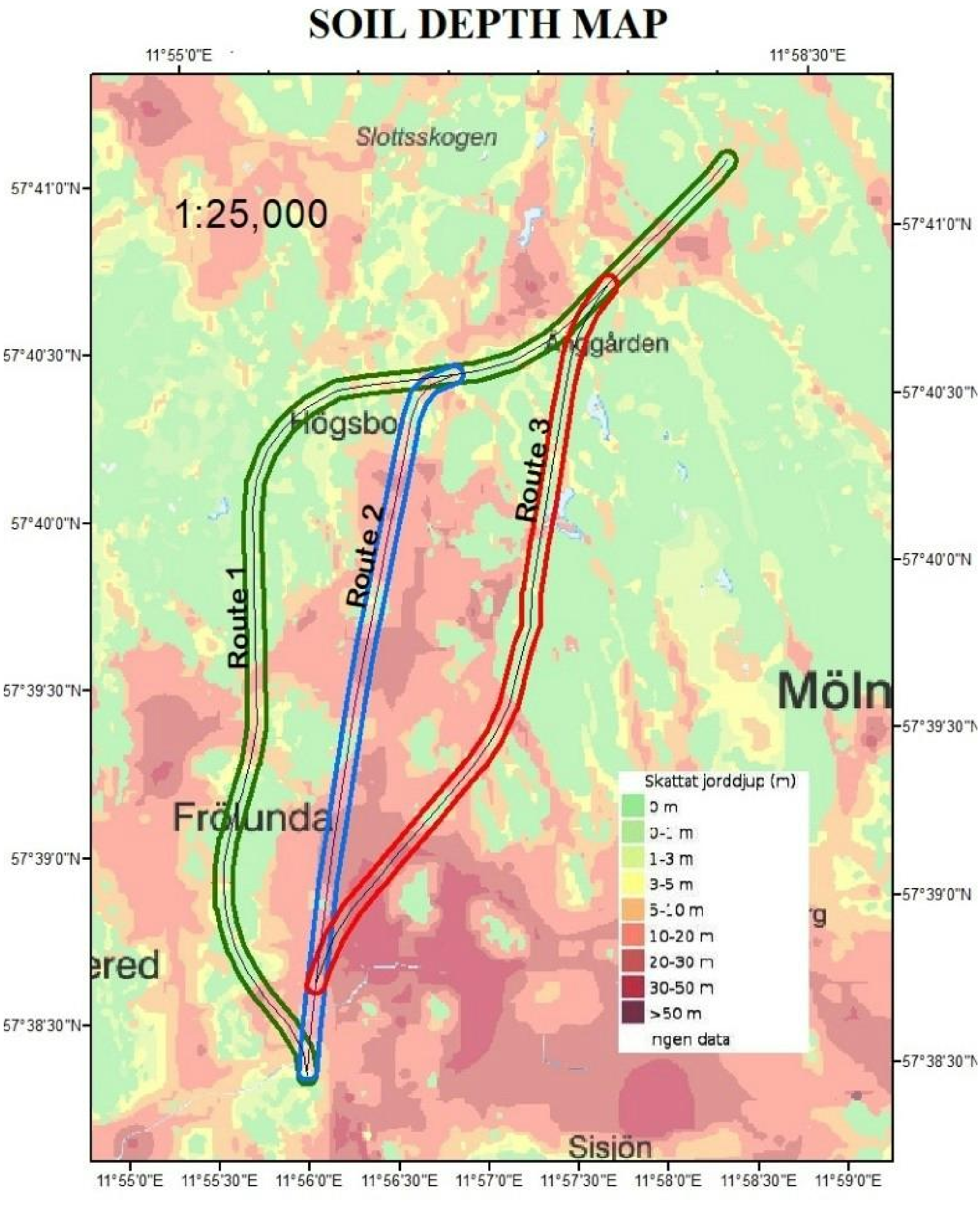


Figure 5.2: GIS map of the soil depth along the possible tunnel sections

5.1.3 Space for Horizontal and Vertical Construction

Because all three tunnel sections are located in the subsurface of a metropolitan area, there is limited access to information regarding confidential horizontal or vertical constructions. Thus, it has been challenging to gather data on underground structures. Although no public information is available on known horizontal constructions like tunnels, it is reasonable to assume the presence of piling in areas with deep clay layers to support large buildings. Tunnel route 1 and 2 have clay with greater soil depth in southern portions and the piling likely extends to the bedrock at its deepest point 4.55.2. As there is a lack of information on subsurface constructions, it is difficult to determine potential conflicts with other existing geosystem services s. However, conflicts between underground structures and utilities such as wires, cables, and pipes could arise as a significant concern especially at entry and exit of all tunnel routes otherwise the tunnels corridors goes much deeper than the space for horizontal pipes and wires. Coordination with local utility providers must be ensured before tunneling considering the need for future expansion of the utility services. If the tunnel is constructed, space conflicts could likely arise if there are plans to build additional underground structures at the same depth. The presence of the tunnel could impede the construction of other structures in that area. As a result, any new horizontal or vertical constructions would need to be adjusted to accommodate the existing tunnel. They may be built either above or below the tunnel to avoid interference and ensure proper functionality of both the tunnel and the additional structures. This adaptation is necessary to optimize the use of space and minimize conflicts between the tunnel and any future underground developments.

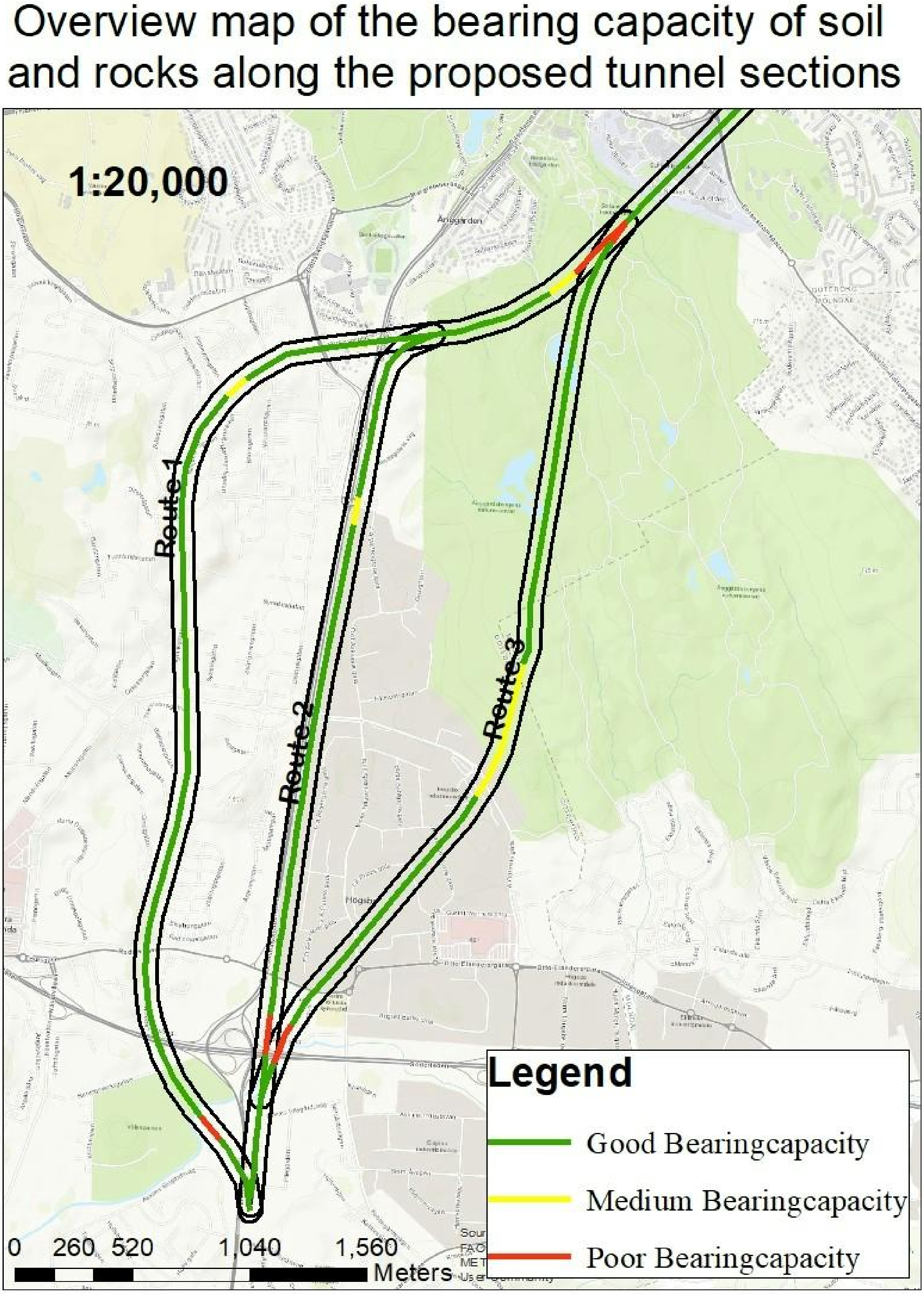


Figure 5.3: The figure reports the overall load-bearing capacity of rocks

5.1.4 Space of Utilities (Wire, cables, pipes)

Typically, lines, cables, and pipes are situated within the uppermost layers of clay and at relatively shallow depths ranging between 1 to 7 meters. Based on Figure 4.1, which indicates that the tunnel section extends deeper than 7 meters and passes through mountainous terrain, it can be inferred that there are no wires, cables, or pipes present in the potential tunnel construction area. At all proposed tunnel entries and exits, there are a few electrical wires and cables which must be taken care of during construction. These wires are at shallow depth however tunnel construction is initiated at the surface. Proper planning, risk assessment, and proactive measures are essential to minimize potential damage and ensure the continued operation of utility lines, cables, and pipes in the vicinity of the tunnel.

However, it is important to consider the potential impact on existing lines, cables, and pipes after the tunnel is built. Careful monitoring and mitigation measures would need to be implemented to prevent such subsidence-related damage and ensure the integrity of the lines, cables, and pipes.

5.1.5 Underground storage

The bedrock along tunnel route 1, as indicated in Figure 5.1, is composed of granite, which is a metamorphic rock. Granite, being a crystalline and relatively impermeable rock, does not possess the necessary high porosity typically found in sedimentary rocks that are suitable for underground storage of substances. Therefore, the bedrock in the area does not offer favorable conditions for underground storage. Similarly, the rocks along the tunnel section of routes 2 and 3 are also impermeable and less porous rock with no utilization for storage purposes. So in this context, the surroundings of all three routes do not possess the capability of underground storage.

Considering this, the potential for underground storage in the area would not be affected by the construction of a tunnel. The unsuitable properties of the bedrock, such as low porosity, make it impractical for underground storage regardless of tunnel construction.

5.2 Cultural Geosystem Services

The tunnel line's 1 known cultural heritage encompasses two stone deposits, which hold significance as they represent cultural elements from prehistoric times. These stone deposits consist of both large and small stones. However, it's important to note that there could potentially be undiscovered cultural heritage sites in the vicinity of the proposed railway route, as indicated in Figure 5.2. According to the Fornsök database, there are records of two possible cultural heritage sites along tunnel line 1: a potential archaeological find site and a potential rock carving (National Museum of Natural History, 2021).

The presence of both known and potential cultural heritage sites raises the possibility of conflicts when considering construction activities such as building facilities, underground constructions, or laying pipes and cables along the railway route. These conflicts may arise due to the need to balance infrastructure development with the preservation of these heritage sites. Decisions regarding how to proceed with construction in these areas must carefully weigh the importance of preserving cultural heritage against the necessity of infrastructure development. This often involves consultations with cultural heritage authorities, archaeologists, and other relevant experts to find solutions that minimize the impact on these valuable historical sites while still meeting the project's objectives (Norrman et al., 2021a).

5.2.1 Known and Unknown cultural heritage

It's reassuring to hear that the construction of the railway section is not expected to bring about significant changes to the known cultural heritage, particularly because these heritage sites are situated on the ground surface. However, the possibility of undiscovered cultural heritage sites is acknowledged, although the likelihood of encountering such sites is considered limited.

This understanding underscores the importance of conducting thorough surveys, assessments, and monitoring during the construction process. By employing careful planning, archaeological assessments, and adherence to cultural heritage preservation protocols, it's possible to mitigate the impact on any unknown cultural heritage sites that may be encountered. This approach allows for responsible development while safeguarding the potential historical and archaeological significance of the area.

5.2.2 Geological heritage

The area where the railway is planned to run does not appear to have any particularly unique or unusual soil or rock types, as indicated in Figures 4.5 and 5.1. Similarly, the soil types found in the area are also typical and commonly found throughout Sweden.

However, it's worth noting the presence of a geotope, specifically a sandstone passage, in relatively close proximity to the tunnel section, as depicted in Figure 5.4. Sandstone is not typically considered a geotope, suggesting that this feature may have some unique or distinctive geological characteristics compared to the surrounding granite and soil formations (Geological Survey of Sweden, 2021c). Further geological investigation and assessment may be necessary to better understand the significance of this sandstone passage in the context of the railway project. If the tunnel route 1 construction takes place, the geological heritage will be damaged due to the blasting operation. Controlled blasting or the use of tunnel boring machines for the construction of tunnels, it is possible to save some of these heritages. Tunnel route 2 and 3 are safe to construct in this specific concern.

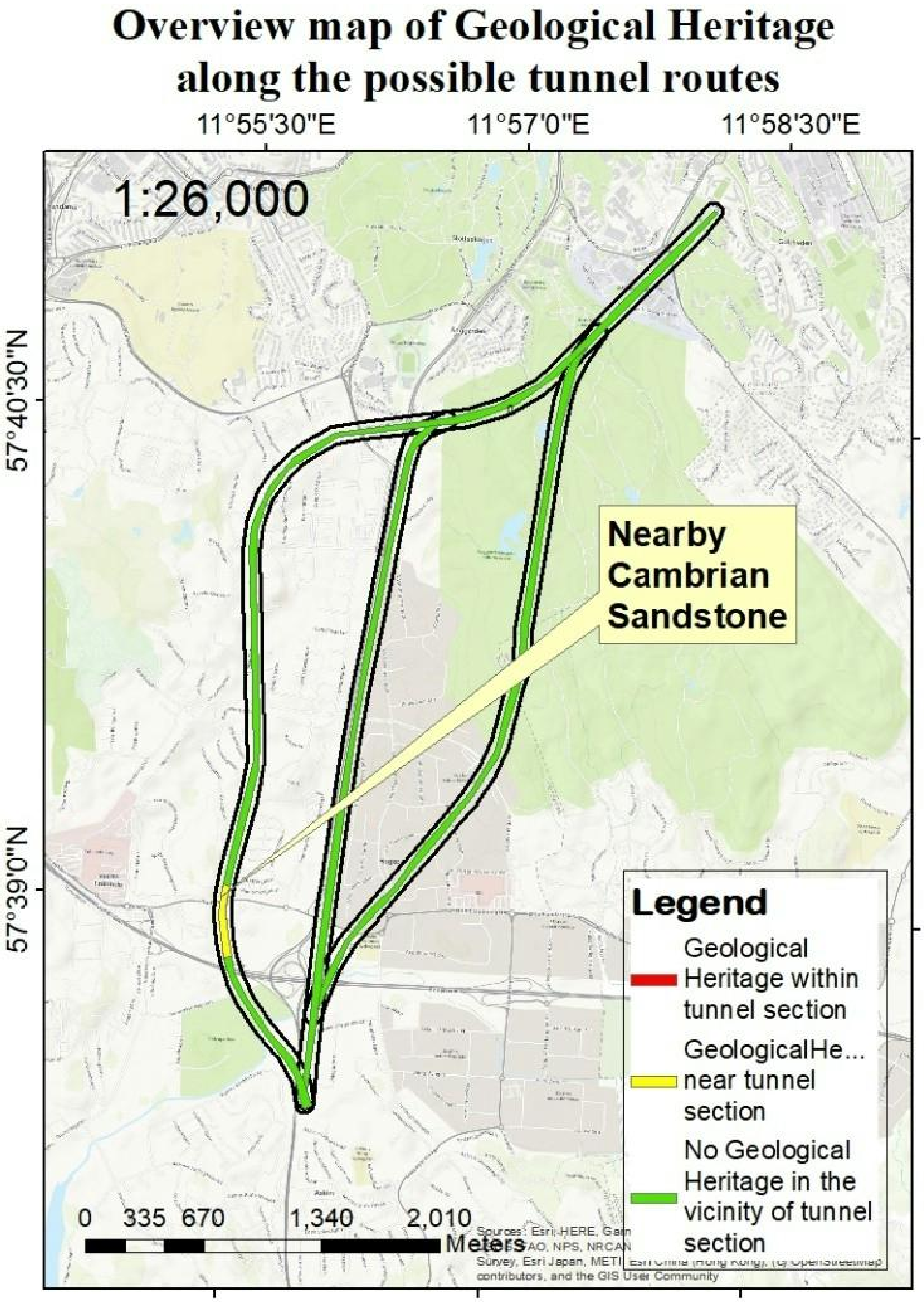


Figure 5.4: Map of geological heritage along the tunnel stretches

5.3 Regulating Geo-system Services

5.3.1 Geo-Energy

According to Figure 5.5, there is a notable presence of energy wells in the area, indicating a potential good for utilizing geo-energy along the entire stretch of the tunnel. This is attributed to the relatively close proximity to the bedrock without extensive layers of clay above it. So using Figures 5.5 and 5.6, a potential for utilization of geo-energy is estimated using GIS. The maps in Figure 5-6 show the quality of Geoenergy along the tunnel routes and also highlight the present geo-energy wells (Geological Survey of Sweden, 2021e).

However, conflicts can arise when energy wells intersect with underground constructions or with existing lines, cables, and pipes. In the case of constructing the tunnel, the existing energy wells that fall within the tunnel's path would likely need to be relocated or decommissioned. Additionally, drilling wells vertically to a depth of 200m or greater can be challenging, raising the possibility of nearby wells being affected due to the construction activities The problem is more prominent along tunnel routes 1 and 2, however, tunnel route 3 has drill well with depths less than 200m.

Moreover, Figure 5.5 indicates that it would be impractical to utilize geo-energy with wells located above the tunnel. The difficulty in drilling wells completely straight into the ground also poses challenges for utilizing geo-energy in close proximity to the tunnel. Considering these factors, the construction of the tunnel would likely require addressing the presence of existing energy wells along the tunnel route and carefully evaluating the potential impact on nearby wells. Furthermore, utilizing geo-energy near the tunnel may face limitations due to drilling constraints and potential disruptions caused by the tunnel construction.

Construction activities may have environmental impacts, such as soil disturbance, which could affect the surrounding area and potentially impact the groundwater quality or contaminate energy well sites. Energy wells may limit access to certain areas for construction equipment and workers. Coordination is needed to ensure access requirements for both construction and energy maintenance are met. Developing effective mitigation strategies to address conflicts, such as reinforcing energy well protection, can be challenging but necessary to resolve conflicts without compromising energy supply or construction progress.

To manage these conflicts effectively, careful planning, collaboration between energy providers and construction teams, thorough risk assessments, and compliance with relevant regulations are essential. It is crucial to prioritize the safety and functionality of energy infrastructure while meeting the infrastructure needs of the project.

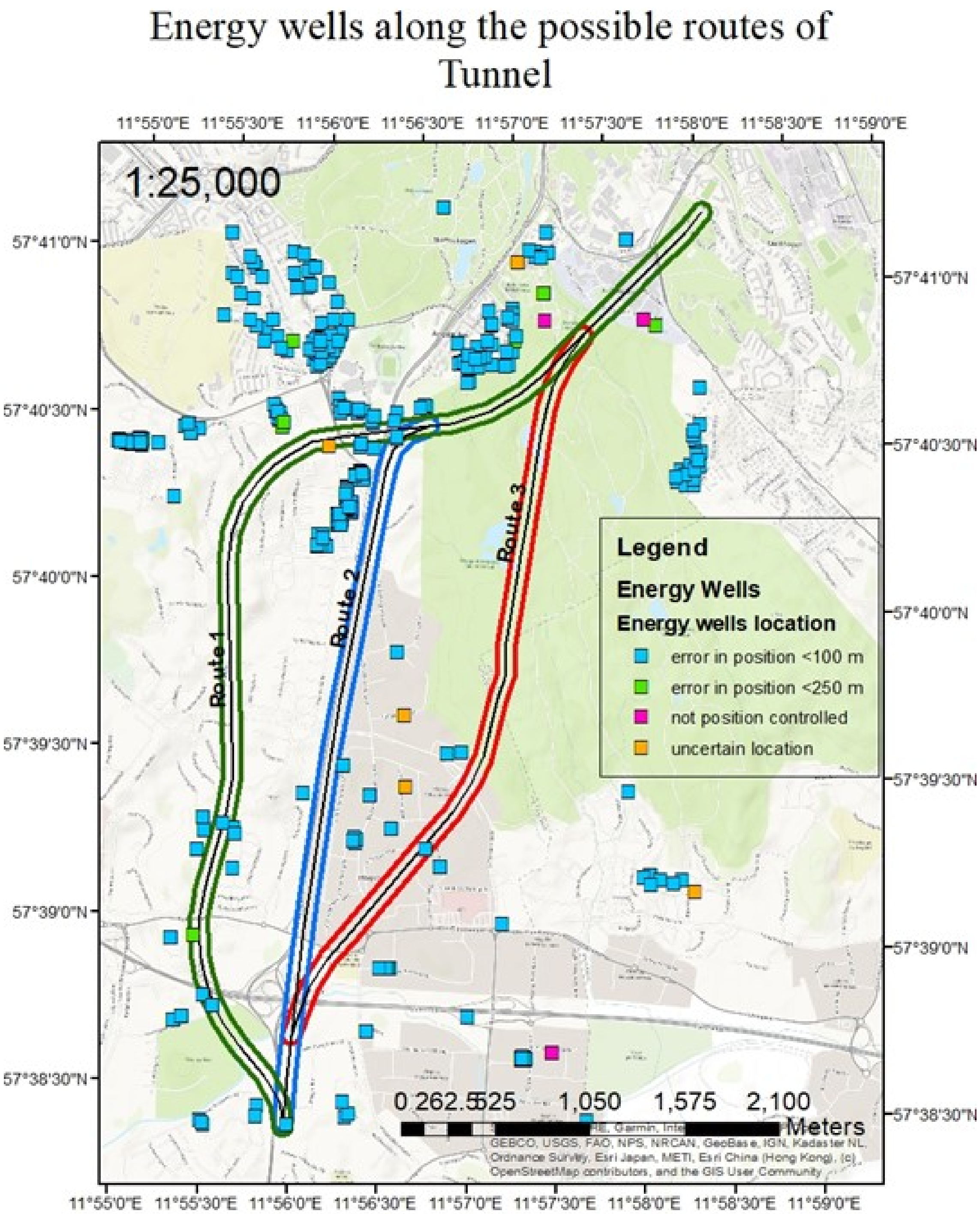
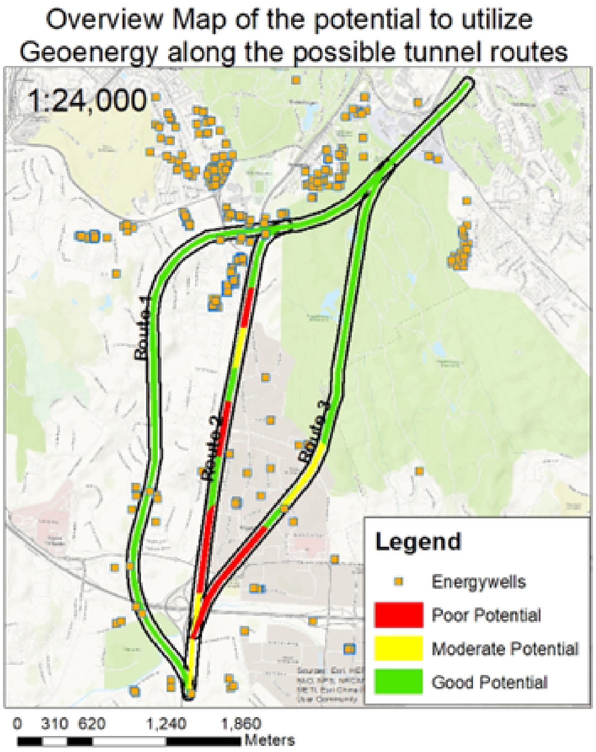


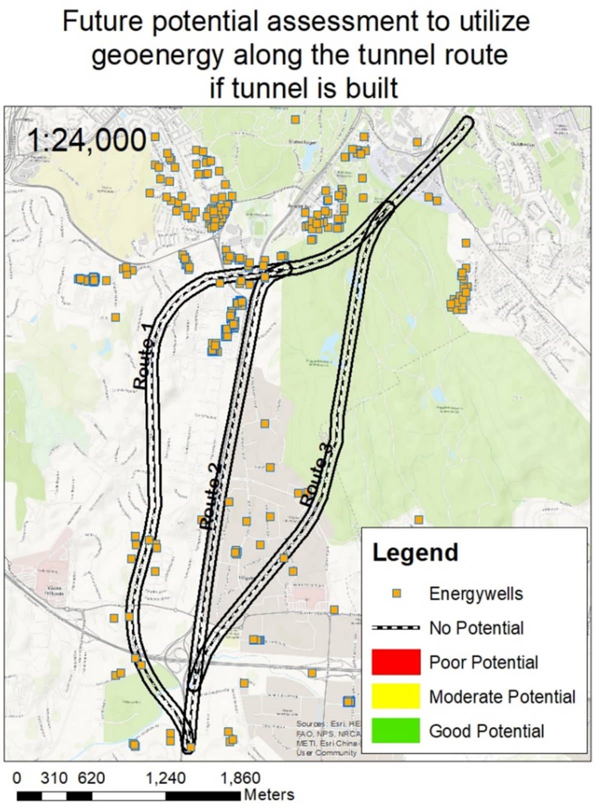
Figure 5.5: Map showing the present energy wells with color depicting error in position

5.3.2 Clean and Safe Soil

According to Figure 5.7, the uranium content along the tunnel cover does not appear to be particularly high. However, the rock in the Änggården area, which is situated after the tunnel corridor, contains an elevated level of uranium. This is noteworthy



(a)



(b)

Figure 5.6: This figure reports the quality of geo-energy and where existing energy wells are located. The map is based on figure 5.1, 5.3 and 5.5

because granite, the type of rock found in Änggården, is known to have relatively high levels of uranium, as indicated by the Swedish Geological Survey in 2022.

The risk of radon gas exposure varies along the route, initially ranging from low to normal. Generally, the radon risk is classified as low, but there is a high-risk area in Änggården. The source map was not available so this information is gathered from the literature review. Figure 5.8 serves as the basis for identifying potentially contaminated areas. The risk identification is based on using the Methodology for Inventorying Contaminated Areas (MIFO method). It is shown as very high, high risk, moderate risk, and low-risk pollution areas. The areas with no risk are also mapped in Figure 5.8. Figure5.8 serves as a contamination map for the risk assessment of pollution of soil in the vicinity of tunnel stretches.

This information highlights the importance of considering uranium and radon risks in the construction and planning of the tunnel, particularly in areas with elevated levels (Geological Survey of Sweden, 2022f). Mitigation measures and safety protocols should be in place to address potential health and safety concerns associated with radon exposure and uranium content during the construction and operation of the tunnel.

The soil and rock in the area are generally considered to have good potential in terms of being clean and safe. According to Figure 5.5, there are only three locations along the tunnel stretch where potential contamination is a concern. But 5.9 shows that soil along tunnel route 2 and 3 are at very high risk of contamination due to presence of high risk contamination.. Tunnel route 1 is safe along maximum path of route. These areas are believed to be contaminated due to various activities that have taken place along the tunnel route. Specifically, the contamination is associated with two dry cleaners and a former gas station (Eurofins, 2017).

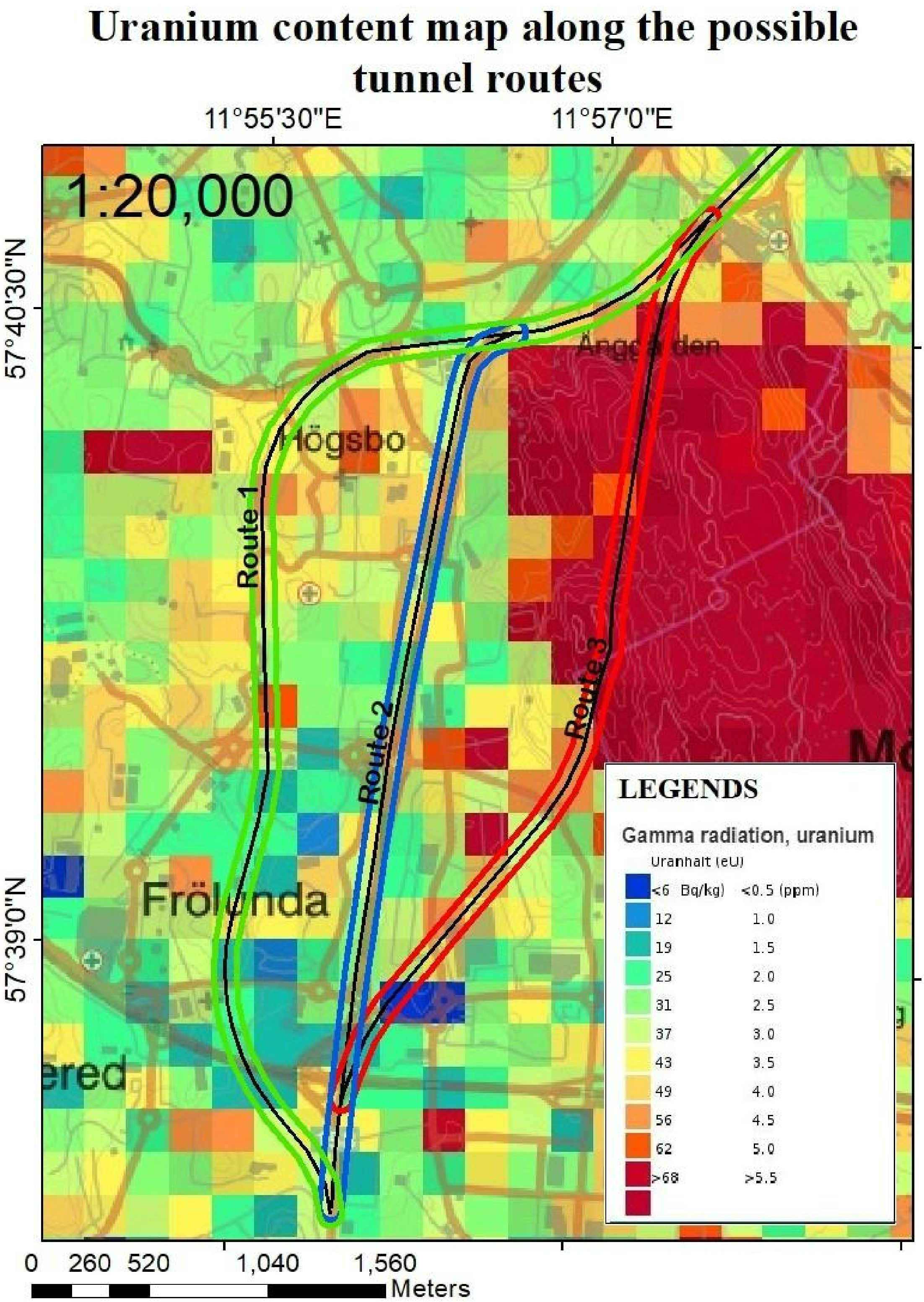


Figure 5.7: Uranium content map along the tunnel stretch (SGU Website)

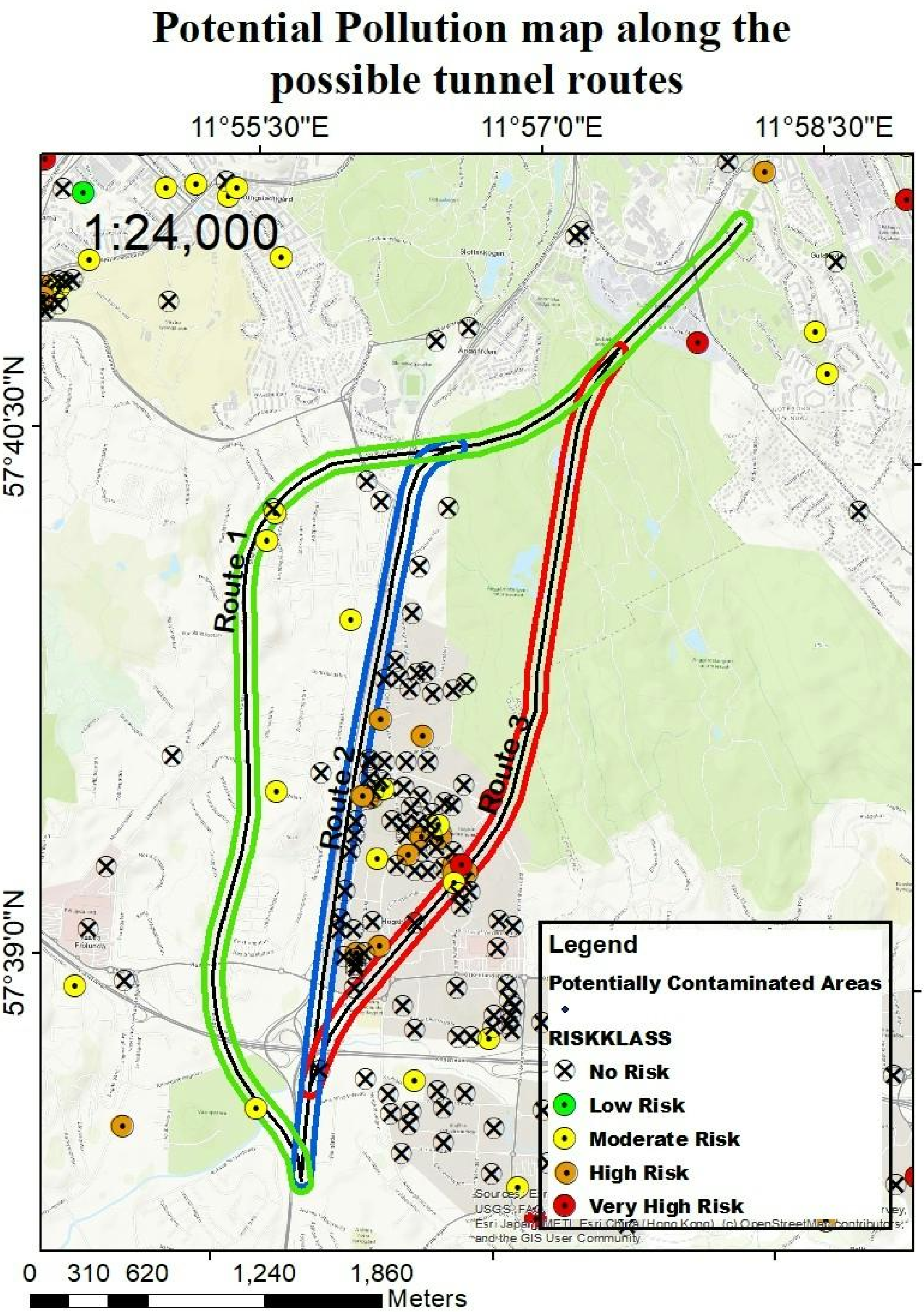


Figure 5.8: GIS Map of the potential pollution along the possible tunnel routes

The pollutants that pose the greatest risk of spreading in this context are chlorinated hydrocarbons, which are commonly used as detergents in dry cleaners. These hydrocarbons are characterized by their liquid nature and their limited ability to dissolve in water (Eurofins, 2017).

The potential for pollutant spread depends on several factors, including the characteristics of the soil and rock layers. When pollutants that are water-soluble are released onto a thick layer of soil, this layer can act as a barrier, preventing contamination from reaching deeper groundwater reservoirs. However, when pollution occurs on a thin layer of soil with underlying rock, the contamination may have a more direct pathway to reach the groundwater, especially through cracks in the rock.

Chlorinated solvents, in particular, have the ability to penetrate deep into the ground due to their heavy nature compared to water. In the case mentioned, where dry cleaners are situated on a thin layer of soil with a maximum depth of five meters (as per soil depth map Figure 5.3), there is a risk of groundwater contamination. These chlorinated solvents can potentially seep into the bedrock and spread to considerable depths, reaching up to a hundred meters or even farther, depending on the extent of the release (Körner & Wahlgren, 2015).

Furthermore, during tunnel construction, there is a risk of mobilizing and spreading pollutants. This can occur when groundwater or even chlorinated hydrocarbons are drained into the tunnel, potentially leading to further contamination concerns.

Given the potential risks associated with these pollutants, careful planning, environmental assessments, and appropriate mitigation measures are essential to protect groundwater quality and prevent the spread of contaminants during and after tunnel construction.

Figure 5.9 shows the potential of pollution spread along the tunnel stretch. Based on the figure, it is assumed that tunnel routes 2 and 3 are more prone to pollution spread as compared to tunnel route 1. Because high-risk pollution areas are present near these tunnel routes. If tunnel route 2 and 3 are constructed, protective lining should be installed to ensure safety against contamination which a big economic concern for the project.

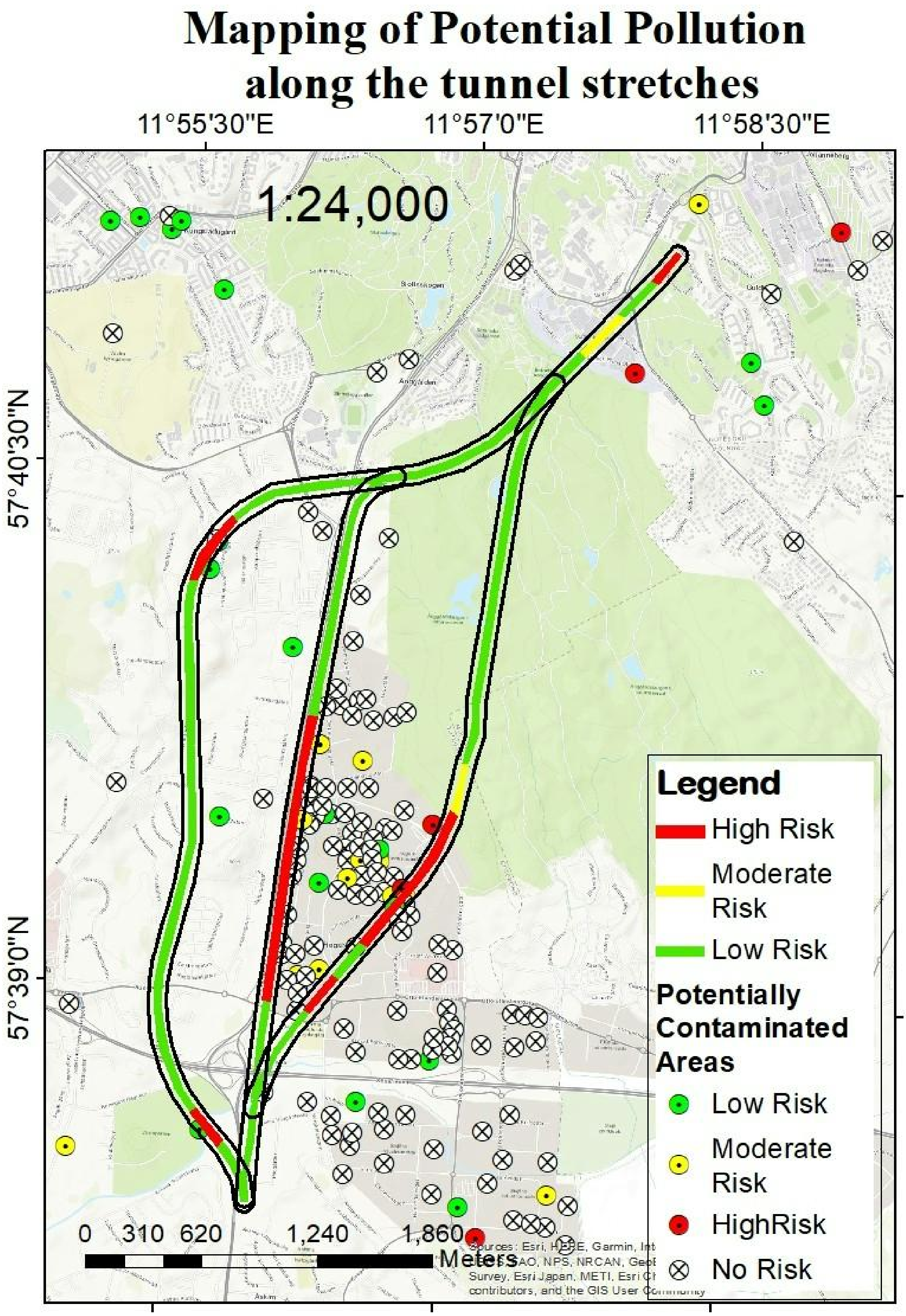


Figure 5.9: Risk potential of pollution spread along the possible tunnel routes

The current situation presents several potential conflicts between pollution and other geosystem services, primarily related to the spread of contamination. Here are some key points highlighting these conflicts:

- **Spread of Pollution:** One of the primary concerns is the potential spread of pollution, especially during tunnel construction. Blasting rocks with high levels of radon can release this radioactive gas into the surrounding environment, posing risks to the health and safety of individuals working on the tunnel project. Contaminated air can also affect nearby communities.

- **Impact on Geomaterial Reuse:** Contaminated geomaterials, such as rock and soil, may have limited potential for reuse, especially in construction projects. The presence of pollutants can hinder the use of these materials as building materials or for other purposes, affecting the sustainability and efficiency of construction projects in the area.

- **Changes in Rock Quality:** The construction of the tunnel may alter the quality of the rock in several ways. For instance, pollution risks may increase after tunnel blasting, particularly in areas like the mountain near Änggården where radon levels are high. Additionally, the transportation and deposition of blasted rock masses may lead to changes in the distribution of rock containing uranium and radon, potentially affecting the geosystem.

- **Mobilization of Chlorinated Hydrocarbons:** During tunnel construction or if the tunnel is not adequately sealed, there is a risk that chlorinated hydrocarbons, which may be present due to prior activities in the area (e.g., dry cleaners), could be mobilized and spread. This can have adverse effects on groundwater quality and environmental health.

  To address these conflicts and mitigate their impacts, it's essential to implement comprehensive risk assessment, management, and prevention strategies (Kuchler et al., 2024). This may include:

  - Rigorous monitoring of air quality during and after tunnel blasting.
  - Proper disposal and containment of contaminated geomaterials.
  - Ensuring the tunnel is well-sealed to prevent the spread of pollutants.
  - Implementing effective measures to prevent the mobilization of chlorinated hydrocarbons.
  - Continual groundwater monitoring to detect any contamination risks.

  Additionally, strict adherence to environmental regulations and safety protocols is imperative to minimize the adverse effects of these conflicts on both human health and the surrounding environment.

5.3.3 Water Retention

The water retention capacity of the soil layers along the intended railway route is considered to be moderate. This assessment takes into account the geological characteristics of the area as depicted in Figures 4.5, 5.1, and 5.3.

The predominant features of the area include hard surfaces, rocks exposed at the surface during the day, connecting postglacial sand or moraine, and deep clay layers. In areas with natural soil, postglacial sand, and moraine, it is assumed that the water retention capacity is sufficiently good to retain moderate amounts of water (Geological Survey of Sweden, 2022c).

This information suggests that the geological composition of the region is such that it can retain a reasonable amount of moisture, which is important for managing groundwater and surface water in the context of railway construction. It's essential to consider these characteristics when planning drainage systems, erosion control measures, and other aspects of infrastructure development to ensure effective water management along the railway route.

The soil type known as **"friction soils"** is noted for its significantly better water retention capacity compared to clay and hard surfaces (Knappett & Craig, 2019). However, there is an interesting dynamic at play here. Despite having good water retention abilities, the poor permeability of clay makes it difficult for friction soils' water retention capacity to be fully utilized. In other words, the water held by the friction soil cannot easily penetrate or flow through the adjacent clay layers.

To optimize the water retention capacity of the area and potentially enhance the geosystem services related to water management, the presence of pipelines, conduits, cables, and pipes that have been buried in the region can be leveraged. If these infrastructure elements are designed with proper drainage systems, they can facilitate water infiltration into the ground and channel excess water away from the area.

It's worth noting that the overall water retention potential of the area is assessed as moderate. Even if a tunnel is constructed in the future, this assessment is unlikely to change significantly. Tunnels are typically not completely sealed, and they may have some level of permeability that allows water to pass through. This feature could potentially contribute to managing water bursting within the tunnel and preventing excessive water buildups insite the tunnel corridor. In summary, understanding the complex interplay between different soil types, permeability, and infrastructure can help optimize water retention and drainage in the area. Leveraging buried infrastructure with proper drainage systems can be a valuable strategy for managing water resources effectively.

5.3.4 Water Filtration Capacity

The water filtering capacity along the possible tunnel route 1 is assessed as poor. This assessment is based on the geological characteristics of the area, as described in Figures 4.5, 5.1 and 5.3.

The primary geological features of the area include hard surfaces, exposed rocks, and clay. These materials are known for their very low permeability, which means that they do not allow water to pass through easily (Eriksson, 2015). Additionally, the presence of thick clay layers further exacerbates the poor filtration capacity (Geological Survey of Sweden, 2021d).

One potential conflict in the area is the presence of buried pipelines, cables, wires, and pipes. These buried infrastructure elements can have a negative impact on natural infiltration, which, in turn, worsens the already poor water filtering ability. The presence of such infrastructure can restrict the movement of water through the soil and rock layers (Geological Survey of Sweden, 2022e).

It's important to note that if a tunnel is constructed in the future, it is unlikely to lead to a significant change in the water filtering ability of the area. This is because the natural permeability of the geological materials in the region is already very low.

Given the poor water filtering capacity, managing water resources effectively in the area is challenging. Mitigation measures, such as proper stormwater management, drainage systems, and erosion control, should be carefully planned and implemented to address potential water-related issues during railway construction and operation. Additionally, minimizing further disruptions to natural infiltration caused by buried infrastructure is essential to maintain the area's hydrological balance.

Tunnel route 3 is also poor in terms of water filteration capacity due to bedrock at the surfece. Tunnel route 2 has good water filteration due to presence of soils, sandy soils of greater depths (Fig. 4.5, 5.1, 5.3).

5.4 Provisioning Geo-system Services

The available geosystem services in the area are underutilized, with only one service, groundwater, being indirectly used. This service is employed to maintain pore pressure and prevent clay settlement. However, the utilization of other geosystem services in the area is limited for several reasons:

- **Limited Potential**: Some geosystem services may not have the potential to be effectively utilized in the specific geological and environmental conditions of the area. For example, if the natural conditions do not support the reliable use of a particular service, it may not be feasible to employ it.

- **Financial Sustainability:** The implementation of certain geosystem services may require significant groundwork, investment, and ongoing maintenance. If the cost of implementing and maintaining a service outweighs the benefits it provides, it may not be financially sustainable for the project.

- **Environmental Constraints:** Environmental considerations, such as potential ecological impacts or regulatory restrictions, can limit the use of certain geosystem services. These constraints may discourage or prohibit the utilization of specific services.

- **Technical Challenges:** Some geosystem services may pose technical challenges that make their implementation complex or unfeasible given the available resources and expertise. It's important to carefully evaluate the feasibility and benefits of utilizing geosystem services in any project. While some services may be underutilized in the area, the decision to use or not use them should be based on a comprehensive assessment of factors such as cost-effectiveness, environmental impact, technical feasibility, and project objectives. In some cases, alternative strategies or technologies may provide more practical solutions to address the project's needs and challenges.

5.4.1 Geothermal Energy

The potential for geothermal energy in the area is relatively poor due to the thick crust in Sweden, which requires very deep drilling to access geothermal heat. As of now, there are no facilities extracting geothermal energy along the tunnel stretch, and therefore, there are no conflicts affecting geothermal energy in the area.

In Gothenburg, there is a trial planned for a geothermal energy system, which is investigating the depth required for accessing geothermal energy. It's important to note that a tunnel constructed along the potential route may restrict the ability to build geothermal energy wells directly above or near the tunnel. Drilling straight down through the tunnel may not be feasible or practical (B. Andersson, 2022) (Geological Survey of Sweden, 2022b).

As a result, geothermal energy boreholes will need to be drilled in alternative locations to utilize this geosystem service effectively. This underscores the need for careful planning and coordination when considering the construction of tunnels and their potential impact on the development and use of renewable energy sources like geothermal energy (Geological Survey of Sweden, 2022b). Ensuring that infrastructure projects do not impede opportunities for sustainable energy generation is an important aspect of responsible planning and development.

5.4.2 Drinking and Process Water Resource

The use of groundwater as a resource for drinking water or industrial processes along the tunnel stretch is currently minimal, with no groundwater wells near the stretch. The geological conditions, as indicated in Figure 5.10, suggest that the area contains smaller groundwater reservoirs rather than large ones. Consequently, the potential for using groundwater as a drinking or process water resource for municipal systems is very low in the area. While there might be some potential for individual wells, the urban environment in the area typically discourages such practices.

Furthermore, the utilization of groundwater as a geosystem service is essentially non-existent along the route. Groundwater quality could be at risk in areas where contamination potential exists.

If the tunnel is constructed, several changes may occur regarding the use of groundwater:

- **Deterioration of Drinking Water Potential:** The construction process, which may involve blasting away rocks, could potentially disrupt groundwater collection in fracture systems. This disruption could reduce the already limited potential for using groundwater as a source of drinking water.

- **Increased Drainage:** Tunnels are challenging to make completely watertight. As a result, the tunnel construction could lead to the drainage of water from the surrounding geological formations into the tunnel. This may further reduce the availability of groundwater resources in the vicinity of the tunnel.

- **Impact on Water Quality:** The tunnel construction process and the potential for contamination in the area may have implications for groundwater quality. Careful management and monitoring of water quality are essential to mitigate any adverse effects.

Given the low potential for using groundwater as a resource in the area, the primary focus should be on minimizing any negative environmental impacts related to groundwater quality and availability during and after tunnel construction. Additionally, it's important to consider alternative sources of water for municipal and industrial needs in the region to ensure a sustainable water supply.

5.4.3 Ground Water Resource

In Chapter 5.4.2, it is noted that the groundwater reservoirs in the area are relatively small and not directly utilized by humans for consumption or industrial processes. Instead, groundwater indirectly contributes to various functions, including providing stability through pore pressure (as discussed by Tremblay in 1990). While plants and animals in the region primarily rely on surface groundwater, some of the precipitation seeps down and becomes stored as groundwater.

The groundwater situation, as presented in Figure 5.10 and documented by (Hjerne, 2021), varies along the length of all three tunnel routes at the southern part. Groundwater levels are within the normal range at the beginning and end of the stretch but fall below the usual levels in the middle. It is crucial to actively maintain groundwater levels, primarily to mitigate the risks associated with subsidence, as emphasized by the Swedish Geological Survey (Geological Survey of Sweden, 2022c).

The presence of buried lines, cables, and pipes may have a slight impact on the groundwater resource as these can potentially drain water away. Furthermore, there is a potential risk that the groundwater resource could deteriorate after the tunnel's construction due to a lowering of groundwater levels. To address this concern, it is imperative to ensure that the tunnel is adequately sealed to prevent water drainage. This issue requires careful consideration and proactive measures, as a declining groundwater resource can lead to settlement problems, particularly in the middle of the stretch where groundwater levels are already lower than usual.

The instability of groundwater levels due to tunneling refers to fluctuations or changes in the depth and behavior of groundwater within an area caused by the construction and operation of tunnels. This instability can have various consequences and impacts on both the environment and the tunneling project itself. During tunnel construction, the excavation process can disrupt the natural flow of groundwater. As tunnels are dug, the surrounding geological formations may be disturbed, potentially causing shifts in groundwater levels and flow. Figure 5.11 shows the stability of current groundwater levels along the tunnel routes. Figure 5.12 shows the instability in groundwater levels after tunnel construction based on figures 4.5, 5.1, and 5.3. Rock permeability is an important factor in changing GW levels. The blasting during tunnel construction propagates present fractures and creates new openings in the rocks, this results in a prominent change in groundwater level after construction. Legal obligations in country code should be follow to reduce these risks during construction.

The instability of groundwater levels due to tunneling is a complex issue that requires careful planning, monitoring, and mitigation efforts to ensure the safety of the tunnel, protect the environment, and minimize any adverse impacts on the local hydrogeology.

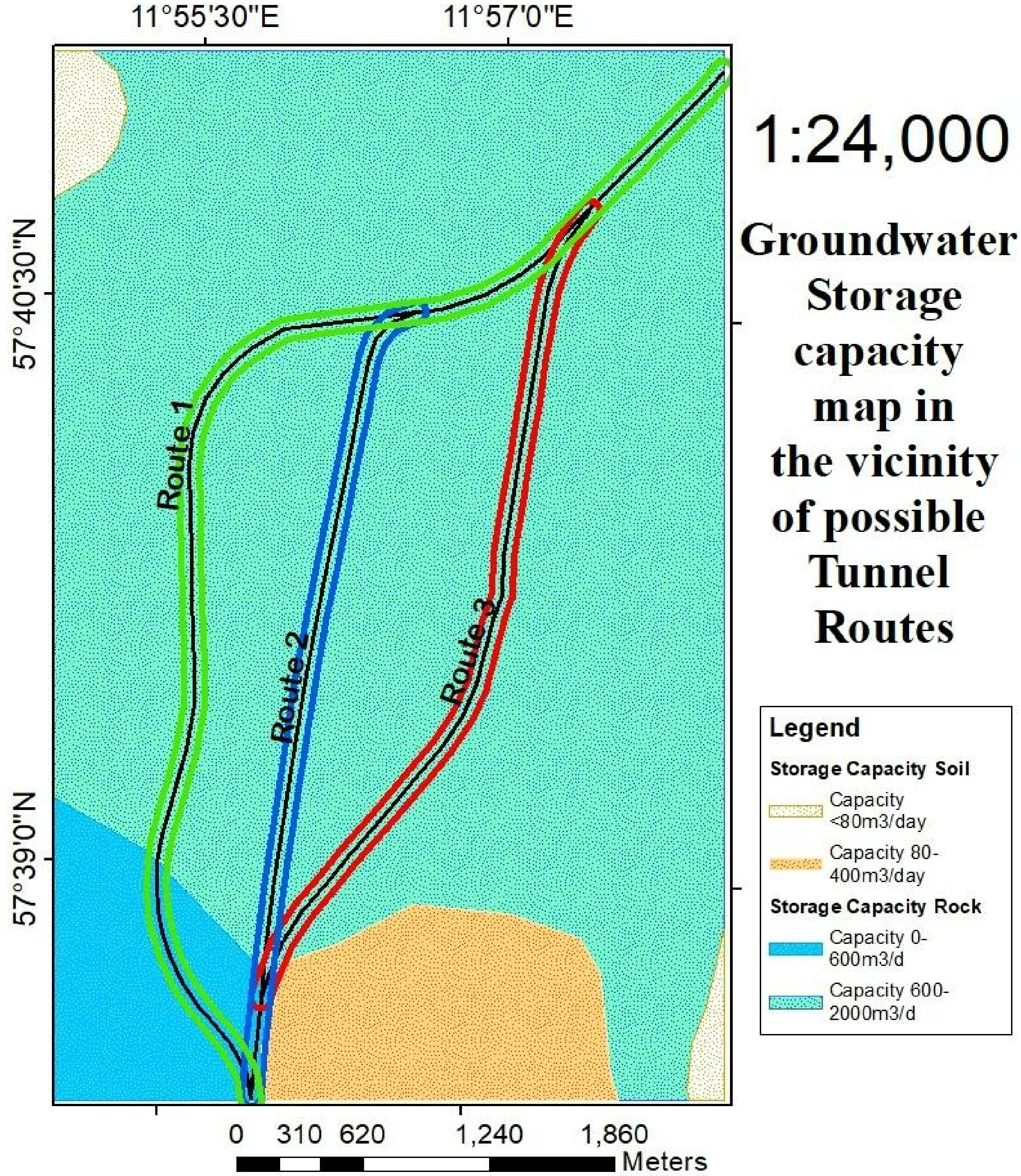


Figure 5.10: Map showing groundwater storage capacity along the possible tunnel routes

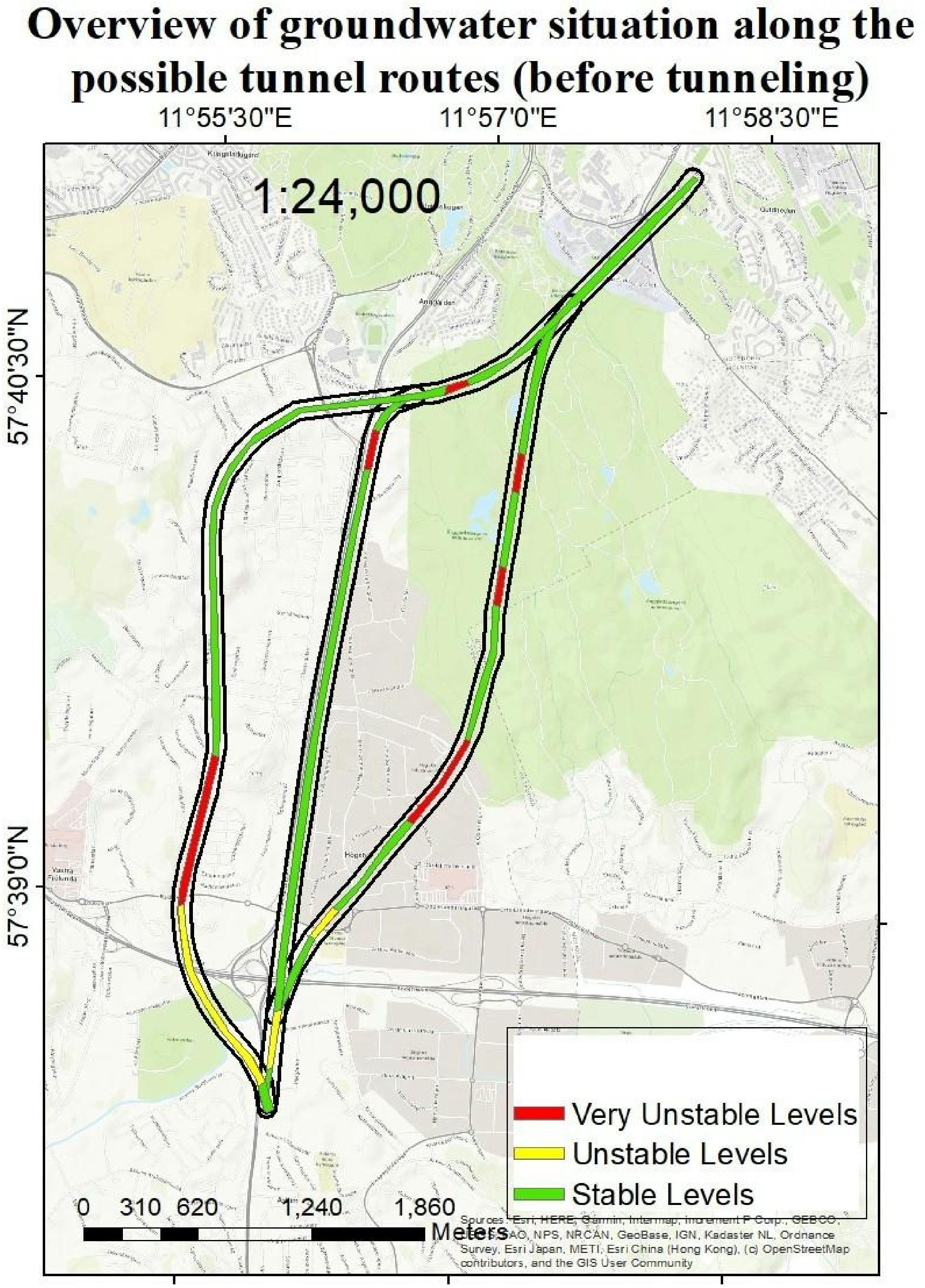


Figure 5.11: GIS based Map of Ground water stability levels before tunnel construction based on 4.5, 5.1 and 5.10

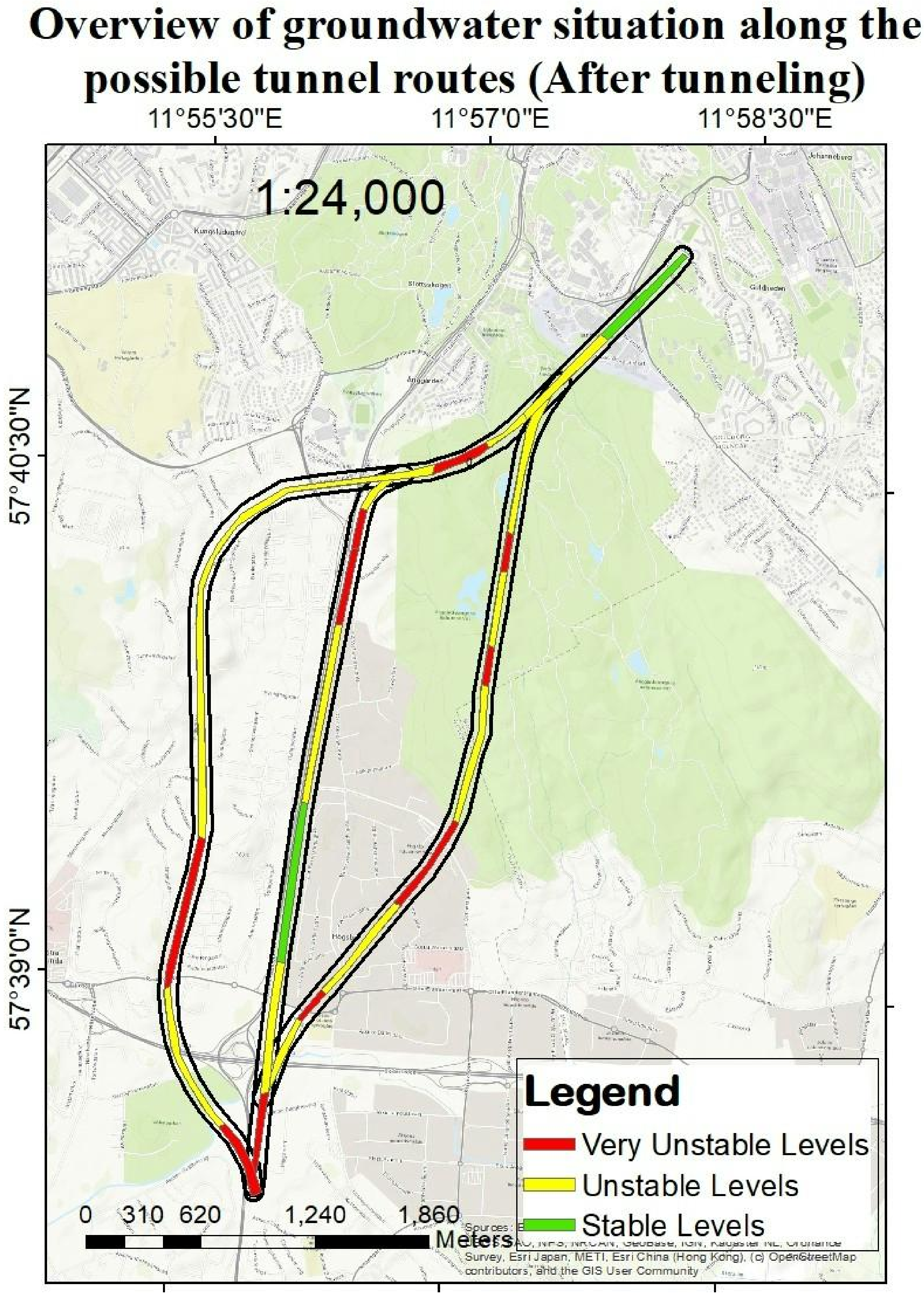


Figure 5.12: GIS based map of Groundwater levels after tunnel construction based on 4.5, 5.1, 5.10

5.4.4 Minerals and Geomaterials

According to Figures 4.5 and 5.1, the material that the potential tunnel routes will traverse is composed of rock. Specifically, the bedrock along the tunnel route 1 consists of tonalite-granodiorite and granodiorite-granite. These types of rock contain various minerals, including quartz, plagioclase, and potassium feldspar, as documented by the Naturhistoriska Riksmuseet in 2021.

This rock material holds the potential to serve as a valuable resource. However, it's important to note that there is no national interest in mining the minerals found in this area, as indicated by the Swedish Geological Survey (Geological Survey of Sweden, 2022d).

The quality of the rock may vary slightly, but it is predominantly suitable for use in road construction (quality class 2), railway construction (quality class 1 and 2), and concrete production (quality class 1), as determined by the Swedish Geological Survey in 2000. Therefore, there is indeed the possibility of utilizing the excavated rock material in the event of tunnel construction. In summary, the rock material in the area offers the potential for reuse and utilization in various construction applications, aligning with the quality standards set for road, railway, and concrete projects. This consideration can be valuable in the planning and sustainability aspects of potential tunneling activities.

The material encountered in the remaining part of the tunnel section is assessed to be of high quality, and the excavated rock material resulting from blasting can be effectively repurposed and put to good use. This presents a valuable synergy or advantage in the project, as it allows for a reduction in the need to extract rock material from either an existing quarry or a newly constructed one (Geological Survey of Sweden, 2021c) (Geological Survey of Sweden, 2021b).

Tunnel route 2 is almost in the same situation as tunnel route 1 according to 5.1 but some of its part is passing through Granite which is a competent rock and used as a construction material (quality class 1). So this is an economical resource. The entire Tunnel route 3 is passing through granite which offers the potential for reuse and utilization in various construction projects, fulfilling the quality standards set for road, railway, and concrete projects.

In other words, the high-quality rock material is found during tunneling of all routes can serve as a sustainable resource that minimizes the environmental impact of quarrying operations. This practice aligns with principles of resource efficiency and environmental conservation by reducing the demand for new excavation sites and conserving natural resources. It also contributes to the overall sustainability and cost-effectiveness of the tunnel construction project.

5.4.5 Multi-criteria Analysis

An impact assessment of the tunnel route alternatives on geosystem services is shown in Table 5.1. A multicriteria analysis method was applied to evaluate the effects.

The scale used represented impact strengths in a qualitative manner using emojis: GOOD captured positive influence, NOT GOOD signified negatives, with NEUTRAL and QUESTION MARK denoting neutral/uncertain consequences. This approach provided a uniform means to compare each route's projected impacts across geosystem services. The table that follows presents the outcomes of the analysis, with theemoji scale visually portraying the determined impact classification for each route-service pairing.

Table 5.1: Geo-system services assessment with Multi Criteria Analysis (MCA)

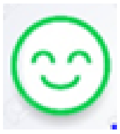
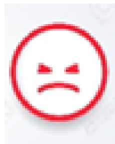
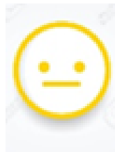
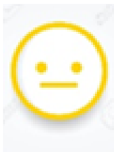
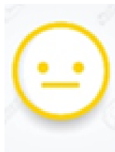
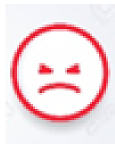
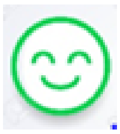
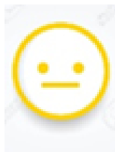
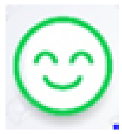
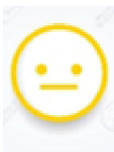
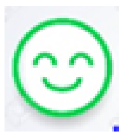
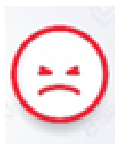
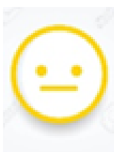
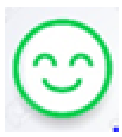
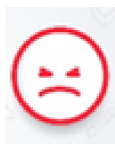
Geosystem Services		**Type of effect**	**Corridor 1**		**Corridor 2**		**Corridor 3**	
			Effect description	**Effect scale**	**Effect description**	**Effect scale**	**Effect description**	**Effect scale**
Supporting Service	Stable platform to build on and within	**Social**	It is expected less traffic, less noise, less accidents etc.		There will be more traffic due to the highway crossing overhead. More noise and vibrations.		Relatively low traffic, but more noise and vibrations.	
		Environmental	No need to transport a lot of material for reinforcement, not much emissions compared to the base case of 'do nothing'.		More reinforcement material will be required, hence, more emissions.		Less reinforcement material will be required and less emissions.	
		Economical	There is no need for substantial reinforcement that is associated with large costs.		Great reinforcement is required to stabilize the surface structures and buildings.		There is no need for substantial reinforcement that is associated with large costs.	
Supporting Service	Underground space for construction	**Social**	Longer commutes, reduced access to public traffic		Shorter commutes, reduced traffic, and increased access to other public transports.		Reduced access to public transport and communities	
		Environmental	Increased underground construction can affect natural diversity and the local ecosystem.		Due to the presence of already existing structures on the surface, less effect on natural diversity and ecosystem.		Increased underground construction can affect natural diversity and the local ecosystem. Deforestation for shaft construction will have a bad effect on air quality.	

Table 5.1: Geo-system services assessment with Multi Criteria Analysis (MCA)

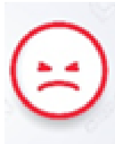
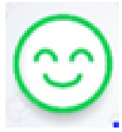
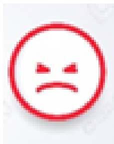
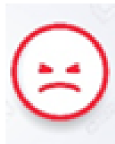
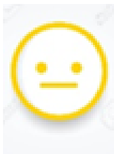
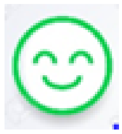
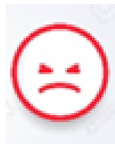
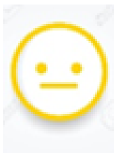
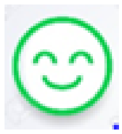
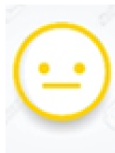
Geosystem Services		**Type of effect**	**Corridor 1**		**Corridor 2**		**Corridor 3**	
			Effect description	**Effect scale**	**Effect description**	**Effect scale**	**Effect description**	**Effect scale**
		Economical	Disposal and storage in the subsurface may devalue the properties and cause safety risks.		Unknown effects as it is not recommended in soil layers.		Dumping sites near/under residential communities pose NIMBY (Not in my backyard) oppositions.	
Supporting Service	Disposal and Storage	**Social**	Disposal and storage in the subsurface may devalue the properties and cause safety risks.		Not recommended in soil layers.		Dumping sites near/under residential communities pose NIMBY (Not in my backyard) oppositions.	
		Environmental	Leakage in groundwater can pollute drinking water and soil. Serious health risk is there. However, risk depends on the type of waste disposed of.		Not recommended in soil with greater depth.		High gamma radiation and uranium content is a big concern to water pollution if not sealed properly.	
		Economical	If construction is done, the high-quality lining should be applied to ensure no leaking, which will be a big cost.		Not recommended in soil with greater depth.		Good quality lining should be applied to ensure no leaking, which is an economical concern.	
Supporting Service	Subsurface Habitats	**Social**	No information.		No information.		No information.	
		Environmental	No information.		No information.		No information.	
		Economical	No information.		No information.		No information.	

Table 5.1: Geo-system services assessment with Multi Criteria Analysis (MCA)

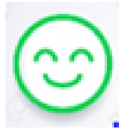
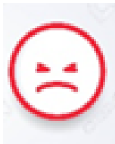
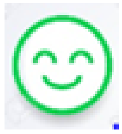
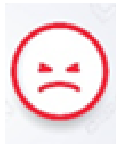
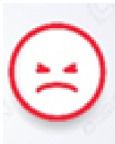
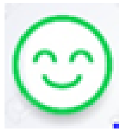
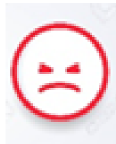
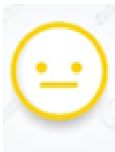
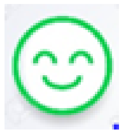
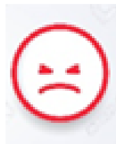
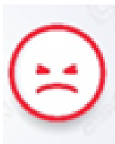
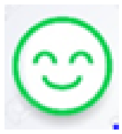
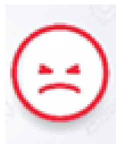
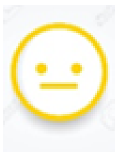
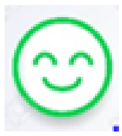
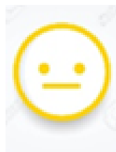
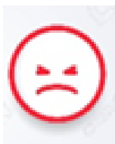
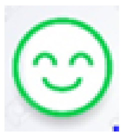
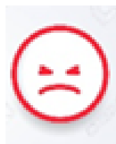
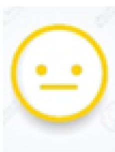
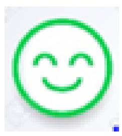
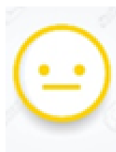
Geosystem Services		**Type of effect**	**Corridor 1**		**Corridor 2**		**Corridor 3**	
			Effect description	**Effect scale**	**Effect description**	**Effect scale**	**Effect description**	**Effect scale**
Regulating Geo-system service	Regulation of Erosion and mass movement	**Social**	No impact due to the presence of rock.		Little impact at some places which can be overcome with timely reinforcement.		No impact due to the presence of rock.	
		Environmental	If ballasting is done, may cause vibrations and dust.		No impact if properly excavated.		If ballasting is done, may cause vibrations and dust.	
		Economical	Excavation cost is added.		Reinforcement is required at some places but no excavation cost is needed.		Excavation cost is added.	
Regulating Geo-system service	Ground Water Quality	**Social**	Mineral dissolution in water may cause serious damage to health and buildings		No risk associated with water quality causing damage to society.		Mineral dissolution and uranium/radon may cause serious damage to health and buildings	
		Environmental	Leaching of metals and acid water causing water pollution due to rock fractures.		Porous media and soil increase the water quality.		Leaching of metals and acid water through rock fractures cause water pollution.	
		Economical	Damage cost to restore groundwater quality.		Positive Impact.		Damage cost to restore groundwater quality.	
Regulating Geo-system service	Regulation of Groundwater Quantity	**Social**	Very unstable ground water levels may cause subsidence and damage building.		Mostly stable levels and low risk of subsidence.		Unstable levels and high chances of subsidence.	
		Environmental	Unstable GW levels disturb the ecosystem.		No Impact.		Unstable GW levels disturb the ecosystem.	

Table 5.1: Geo-system services assessment with Multi Criteria Analysis (MCA)

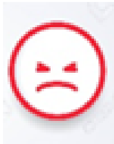
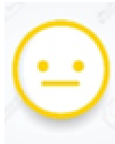
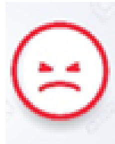
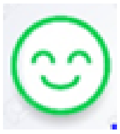
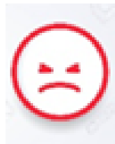
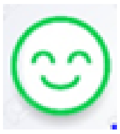
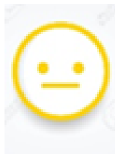
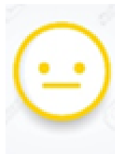
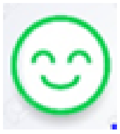
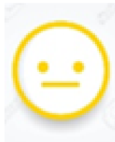
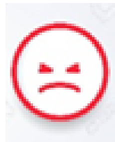
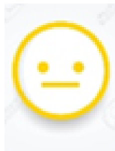
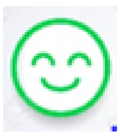
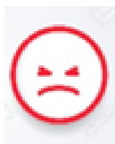
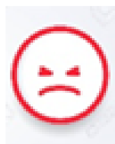
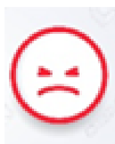
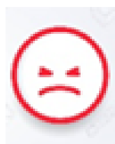
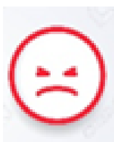
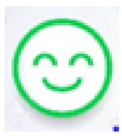
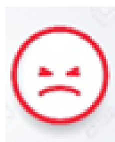
Geosystem Services		**Type of effect**	**Corridor 1**		**Corridor 2**		**Corridor 3**	
			Effect description	**Effect scale**	**Effect description**	**Effect scale**	**Effect description**	**Effect scale**
		Economical	Tunnel Lining cost to ensure no flushing of water in the tunnel.		Cost for strong reinforcement to ensure no water infiltration.		Tunnel Lining cost to ensure no flushing of water in the tunnel.	
Regulating Geo-system service	Regulation of Temperature and Underground thermal storage	**Social**	Good source of heating and cooling of households.		Moderate resources of heating and cooling of households.		Not enough resources to provide heating and cooling services.	
		Environmental	Closer to bedrock, storage capacity is good and can be resourceful in cold weather.		Moderate potential to provide enough regulation of temperature.		Moderate potential to provide enough regulation of temperature.	
		Economical	Construction cost of new wells is not planned.		Construction cost of new wells should be part of the planning.		Construction cost of new wells should be part of the planning.	
Regulating Geo-system service	Regulation of soil and bedrock chemistry	**Social**	Unknown Impact.		Soil is present and soil chemistry affects the pollution.		Unknown Impact.	
		Environmental	No risk of soil and bedrock chemistry change as the tunnel will be at greater depth.		The Risk of soil pollution is higher where soil depth is greater.		High risk of soil contamination and bedrock chemistry change due to high uranium/radon.	
		Economical	No precaution needed thus no extra cost of the project.		Lining cost to ensure no leakage.		High cost for a very strong Lining to stop radon and uranium contamination.	
		Social	Loss of some aquifers may pose drinking water deficiency.		No loss of aquifers due to the presence of soil.		Loss of some aquifers may cause drinking water deficiency.	

Table 5.1: Geo-system services assessment with Multi Criteria Analysis (MCA)

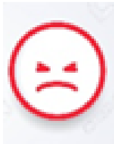
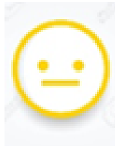
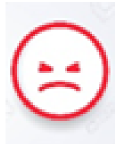
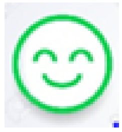
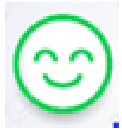
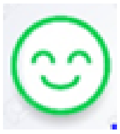
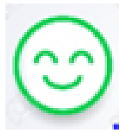
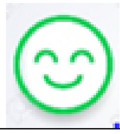
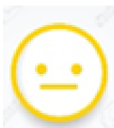
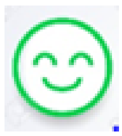
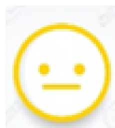
Geosystem Services		**Type of effect**	**Corridor 1**		**Corridor 2**		**Corridor 3**	
			Effect description	**Effect scale**	**Effect description**	**Effect scale**	**Effect description**	**Effect scale**
Provisioning Geosystems	Groundwater resources for drinking and as a material (industrial and irrigation purposes)	**Environmental**	Unknown Impact		Positive Impact due to greater soil depths.		Unknown Impact	
		Economical	Reinforcement cost to protect rock-bearing aquifers.		Drinking water level may deplete due to excavation, and controlled blasting costs.		Reinforcement cost to protect rock-bearing aquifers.	
Provisioning Geosystems	Extraction of Geomaterials	**Social**	No Geomaterials of national interest		No Geomaterials of national interest.		No Geomaterials of national interest	
		Environmental	No loss to ecosystem and natural resource.		No loss to the ecosystem and natural resources		No loss to the ecosystem and natural resource	
		Economical	No excavation cost for geomaterial extraction.		No excavation cost for geomaterial extraction.		No excavation cost for geomaterial extraction.	
Provisioning Geosystems	Fossil Energy resources and storage	**Social**	No Information.		No Information.		No Information.	
		Environmental	No Information.		No Information.		No Information.	
		Economical	No Information.		No Information.		No Information.	
		Social	No resources to provide better heating and cooling facilities for the community.		Moderate resource but no potential is present for good facilitation.		No resources to provide better heating and cooling facilities for the community.	

Table 5.1: Geo-system services assessment with Multi Criteria Analysis (MCA)

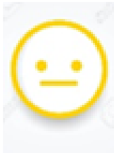
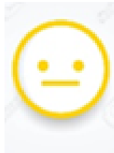
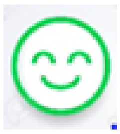
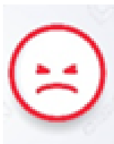
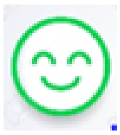
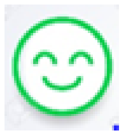
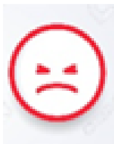
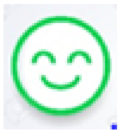
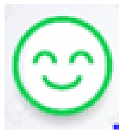
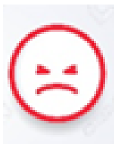
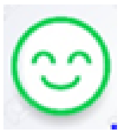
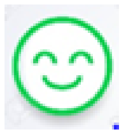
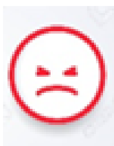
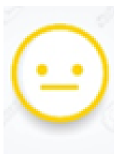
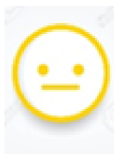
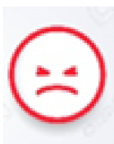
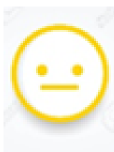
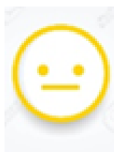
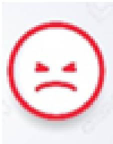
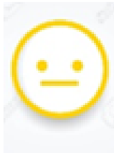
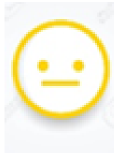
Geosystem Services		**Type of effect**	**Corridor 1**		**Corridor 2**		**Corridor 3**	
			Effect description	**Effect scale**	**Effect description**	**Effect scale**	**Effect description**	**Effect scale**
Provisioning Geosystems	Geothermal Resources	**Environmental**	Crustal thickness is high so no change in the environment.		Positive impact due to more soil depth.		Crustal thickness is high so no change in the environment.	
		Economical	Unknown Impact.		Positive Impact if resources are getting into use after excavation.		Unknown Impact.	
Cultural Geosystems	Historical, recreational and sacred sites	**Social**	Loss of known cultural sites affects community attraction and tourism and research at the international level.		Cultural sites at shallow depth may not be affected and no societal impact will be observed.		Cultural sites at shallow depth may not be affected and no societal impact will be observed.	
		Environmental	Loss of unknown sacred sites leave a negative impact on environment		Positive Impact		Positive Impact	
		Economical	Tourism attraction and research interest will be lost which affect the national economy.		Tourism attraction and research projects will be enhanced once the cultural places are explored.		Tourism attraction and research projects will be enhanced once the cultural places are explored.	
Cultural Geosystems	Geological Heritage	**Social**	Sandstone walkway if destroyed will lose international research interest		No Effect.		No Effect	
		Environmental	Geological diversity and history will be destroyed.		No Effect		No Effect	

Table 5.1: Geo-system services assessment with Multi Criteria Analysis (MCA)

Geosystem Services		**Type of effect**	**Corridor 1**		**Corridor 2**		**Corridor 3**	
			Effect description	**Effect scale**	**Effect description**	**Effect scale**	**Effect description**	**Effect scale**
		Economical	Tourism attraction and international research interest will be lost which affect the national economy.		No Effect.		No Effect.	

The multi-criteria analysis table allowed for a comparison of the potential social, environmental, and economic effects of the three proposed tunnel routes. It provided a perspective on how each route might impact these different assessment criteria. The table format facilitated an overview of the relative performance of the tunnel options across the important social, environmental, and economic dimensions considered in the evaluation.

6

Discussion

Currently, the utilization of subsurface resources is often not adequately considered during the initial planning stages; it typically operates on a "first come, first served" basis (Norrman et al., 2021a). To ensure the creation of sustainable communities in the long term, it becomes crucial to give greater consideration to underground resources during the planning phase.

As our population continues to grow, we can anticipate a rise in housing demand and increased traffic congestion on our roads. This trend is expected to lead to more significant challenges in terms of urban densification. Consequently, emphasizing and integrating underground resources in the early planning stages is essential to address these evolving challenges effectively.

The construction of any one of these possible tunnel corridors is anticipated to result in a decreased need for certain geosystem services. This is because both horizontal and vertical underground structures are expected to conflict with the tunnel, as no other underground constructions will be feasible at the same depth within the tunnel corridor.

The feasibility of utilizing geo-energy along the tunnel route 2 and 3 is expected to be extremely challenging, if not entirely unfeasible. This is primarily due to the tunnel effectively preventing the installation of energy wells. Even existing energy wells located within the tunnel corridor would need to be decommissioned to facilitate the construction of the tunnel. The same holds true for energy wells in the vicinity of the study area, some of which may have been drilled at oblique angles. Similarly, tunnel route 1 is also affecting the location of energy wells in the north side but most of the path is feasible to utilize geo-energy.

The conditions for implementing geothermal energy are unfavorable even before the tunnel's construction, and they are likely to become even more challenging or impossible once the tunnel is in place. However, one potential avenue for geo-energy utilization is to drill wells from the bottom of the tunnel and leverage the tunnel's infrastructure for multifunctional purposes.

There is a potential hazard that groundwater contamination may become mobilized during the construction of tunnel Route 1. The most significant concern arises if tunnel construction has the capability to mobilize and transport chlorinated hydrocarbons originating from nearby dry-cleaning facilities. This situation could pose workplace safety challenges and result in the broader dispersion of these substances beyond their initial boundaries. The tunnel route 3 is passing from the area with a very high risk of contamination thus the construction might trigger the leakage of contaminants into groundwater and surrounding soils. Tunnel Route 2 is also challenging but passes through moderate and low-risk areas.

The current project has offered valuable insights, encompassing both positive experiences and challenges. One significant advantage is its primary objective: a meticulous examination of subterranean resources. This assumes heightened importance, particularly in the context of increasing urban densification. Properly managing and efficiently harnessing underground resources can result in the creation of additional space above the Earth's surface. An earlier report, titled "Integrating underground services into planning" (Norrman et al., 2021b), also delves into the assessment of subsoil resources, and a notable development in comparison with this report is the utilization of a comprehensive color-coded system throughout the entire study area.

This work has certain limitations that should be noted. Firstly, in the general plan, a 100-meter corridor was designated around the route 1. However, this width may not be the most suitable choice, as the delineation area is likely to fluctuate depending on geological conditions and the specific geosystem service under investigation. In reality, the delineation area is expected to be smaller due to the majority of the tunnel passing through mountainous terrain, and the initial choice of a slightly larger area to avoid being overly restrictive. However the geological challenges during construction In regard to the evaluation of space conflicts between horizontal and vertical underground structures and the tunnel, the absence of data regarding potentially classified structures introduces a level of uncertainty. This underscores the need for a comprehensive review and the inclusion of this information to ensure a more comprehensive and accurate assessment of potential conflicts and their resolutions. Addressing these limitations will contribute to a more robust and informed analysis of the project's feasibility and potential impacts.

7

Conclusion

If Tunnel Corridor 1 is constructed, it is anticipated that several geosystem services will face challenges and pose negative effect on environment, society and economy. Primarily, constructing horizontal or vertical underground structures at the same depth as the tunnel would not be feasible. Additionally, geo-energy wells within and near the tunnel corridor would need to be relocated which is a big economical concern. Extracting geo-energy in the area, including geothermal energy, would become significantly challenging. There is also a risk of mobilization and dispersion of chlorinated hydrocarbons from dry cleaners if the tunnel is not properly sealed. Lastly, transporting geomaterial, including contaminated material and rock with high radon and uranium content, would entail additional costs both from a financial and environmental perspective. Shown in Table A-3 in the appendix.

Table A-2 in the appendix shows the assessment of geo-system services along corridor 2. The groundwater resource is at risk of deterioration, particularly if the tunnel is not adequately sealed. The reinforcement will result in rise in project cost. If not sealed properly, the tunnel could act as a conduit, potentially leading to reduced water levels in the aquifer and an increased risk of subsidence on the surface due to the inability to maintain pore water pressure in the clay. This may effect the residential societies by reducing their water utilities. Since corridor 2 passes through high-depth soils including clays and glacial sand proper lining of the tunnel should be ensured if built. There are two or three energy wells that need to be relocated. Overall, the construction of tunnel corridor 2 is a high cost project as compared to corridor 1 and 3 located in rocks.

The assessment of corridor 3 for the geo-system services is also elaborated in Table A-3 . A major part of the tunnel runs through rock with good bearing capacity and low chances of settlement. Thus its an economical option and less societal harm. However, the area has very high contents of uranium which may lead to high exposure to harmful radiation after excavation. In reference to Figure 5.9, route 3 passes from a high-risk pollution area which is a big hurdle in the way of construction. Furthermore, there are 5 energy wells within a few meters across the tunnel corridor (figure 5.5), which will be abandoned or relocated. The tunnel corridor 3 is a big environmental challenge due to high risk contamination in the way.

While the mapping conducted in this study is specific to the site, some of the findings hold broader applicability to areas with similar geological conditions. Several key methodological insights have emerged:

- The concept of geo-system services, which complements the more commonly employed idea of ecosystem services, proves valuable. It has the potential to facilitate effective communication between engineers and planners regarding subsurface considerations and underscores its significance.

- Mapping the attributes of the subsurface involves gathering data from multiple databases and interpreting materials. This underscores the need, at the municipal or city level, for organized, digital 3D archives that provide easy access to information in relevant formats.

- Adopting a perspective that recognizes the underground's multifaceted resources, functions, and services makes subsurface planning relevant not only in metropolitan areas but also in smaller municipalities where underground construction may be limited but where other subsurface qualities play a role.

- Building upon the insights gained from this pilot study, further work is recommended to:

  - Delve deeper into the concept of geosystem services and its practical utility in the context of urban planning.

  - Determine the optimal planning level (national, regional, or municipal) for managing different geosystem services effectively.

  - Develop methodologies and tools to assist planners in addressing conflicts arising from competing demands for physical space and other subsurface resources.

The MCA table provided an insight of all three possible tunnel routes with respect to its social, environmental and economic impact. This approach is very particular for selection of best route for railway tunnel. Considering all the positive and negative effects of tunnel excavation on geosystem services, tunnel route 3 seems the best option in many prospects. The one reason behind selecting this route as best suitable could be the absence of any cultural and geoheritage which might be disturbed due to excavation. This is the most important reason for not selecting tunnel route 1. Secondly, the route is passing through hard rock at maximum portion, which ensure good bearing capacity so tunnel lining or stability cost is minimum in this project. The big issue in this tunnel route is the presence of high contaminant zone especially uranium content. The rock bearing uranium when exposed could pose serious health risks. Another reason for not choosing this route is the absence of energy wells. So in this research, tunnel route 2 seems the best option. Although it is not an economical route (reinforcement and lining cost) but it is safe and most suitable with respect to all other geo-system services. This research recommends that Tunnel Route 2 is least effecting our geosystem services and the supporting and provisioning services are well justifying the construction of this route. At surface, there is a highway and traffic regulating facilities are available, bus stations are present for easy commute to other city parts, so it is the best route in every perspective.

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A

Appendix 1

Table A.1: Assessment of the potential of geosystem services before and after construction of possible tunnel route 1

Geosystem Services		**Corridor 1**	**Impact**
REGULATING SERVICES	Regulation of erosion and mass movements	Good quality rock is present so low chances of erosion and mass movements	Due to ballasting, disturbance in rock may cause fracture propagation
	Regulation of groundwater quantity	Present levels are normal	Lowering of water levels due to high infiltration rate
	Regulation of groundwater quality	Present quality of water is good with low to minimum contamination	Low to moderate risk of groundwater pollution
	Regulation of temperature by underground thermal storage capacity	Good condition as it is relatively close to the bedrock	Reduced access to the service
	Regulation of soil and bedrock chemistry, including chemical weathering	Low to moderate risk of contamination of soil	Soil chemistry will be unchanged as the tunnel will be at greater depth

Geosystem Services		Corridor 1	Impact
SUPPORTING SERVICES	Stable platform to build on and within	Rock in the area is competent and hard to excavate in	Unchanged
	Underground space	Rock in the area is not suitable for underground construction	Unchanged
	Disposal and storage	Rock is not suitable for disposal and storage	Unchanged
	Subsurface habitats	No Information	No information
PROVISIONING SERVICES	Groundwater resources for drinking and as a material (industrial and irrigation purposes)	Bad condition as groundwater is only found in small reservoirs	Unchanged
	Extraction of geomaterials	There is no geomaterial of national interest	Unchanged
	Fossil energy resources and storage	No Information	No Information
	Geothermal resources	Poor resources as bedrock are at the surface and crustal thickness is very high	Unchanged
CULTURAL SERVICES	Historical, recreational, and sacred sites	There are some known and unknown cultural sites in the tunnel corridor	Assumed not to be affected as they lie at shallow depths

Geosystem Services		Corridor 1	Impact
	Geo-scientific and Geo-educational resources	Sandstone walkway in the tunnel corridor	Some unidentified parts can be damaged during construction

Table A.2: Assessment of the potential of geosystem services before and after construction of possible tunnel route 2

Geosystem Services		Corridor 2	Impact
REGULATING SERVICES	Regulation of erosion and mass movements	Soil depth is greater along some of the portions of corridor 2(20-30m) so little chance of soil erosion and mass movement are there.	Underground ballasting and excavation may disturb soils at some places
	Regulation of groundwater quantity	Present levels are normal	Lowering of water levels due to high infiltration rate
	Regulation of groundwater quality	Present quality of water is normal with low to medium chances of contamination	Moderate risk of groundwater pollution
	Regulation of temperature by underground thermal storage capacity	Good condition as it is relatively close to the bedrock	Reduced access to the service
	Regulation of soil and bedrock chemistry, incl. chemical weathering	Low to moderate risk of contamination of soil	Soil chemistry will be unchanged as the tunnel will be at greater depth
	Stable platform to build on and within	Rock in the area is competent and hard to excavate in	Unchanged

Geosystem Services		Corridor 2	Impact
SUPPORTING SERVICES	Underground space	Rock in the area is not suitable for underground construction	Unchanged
	Disposal and storage	Rock is not suitable for disposal and storage	Unchanged
	Subsurface habitats	No Information	No information
PROVISIONING SERVICES	Groundwater resources for drinking and as a material (industrial and irrigation purposes)	Bad condition as groundwater is only found in small reservoirs	Unchanged
	Extraction of geomaterials	There is no geomaterial of national interest	Unchanged
	Fossil energy resources and storage	No Information	No Information
CULTURAL SERVICES	Historical, recreational, and sacred sites	There are some known and unknown cultural sites in the tunnel corridor	Assumed not to be affected as they lie at shallow depths
	Geo-scientific and Geo-educational resources	No geological heritage in the way of the tunnel corridor	No impact

Table A.3: Assessment of the potential of geosystem services before and after construction of possible tunnel route 3

Geosystem Services		**Corridor 3**	**Impact**
REGULATING SERVICES	Regulation of erosion and mass movements	Most of the tunnel part is passing through rock of good quality, No chance of soil erosion and mass movement	Due to ballasting, disturbance in rock may cause fracture propagation
	Regulation of groundwater quantity	Present levels are normal	Lowering of water levels due to high infiltration rate
	Regulation of groundwater quality	Present quality of water is normal with low to medium chances of contamination	High risk of groundwater pollution due to high radon and uranium content in the area
	Regulation of temperature by underground thermal storage capacity	Good condition as it is relatively close to the bedrock	Reduced access to the service
	Regulation of soil and bedrock chemistry, incl. chemical weathering	High risk of soil contamination due to high uranium content and pollution in the area	Most of the area is rocky so along a short tunnel corridor, a low-depth soil is prone to contamination
SUPPORTING SERVICES	Stable platform to build on and within	Rock in the area is competent and hard to excavate	Unchanged
	Underground space	Rock in the area is not suitable for underground construction due to high contamination	Unchanged

Geosystem Services		Corridor 3	Impact
	Disposal and storage	Rock is not suitable for disposal and storage due to high gamma radiation.	Unchanged
	Subsurface habitats	No Information	No information
PROVISIONING SERVICES	Groundwater resources for drinking and as a material (industrial and irrigation purposes)	Bad condition as groundwater is only found in small reservoirs	Unchanged
	Extraction of geomaterials	There is no geomaterial of national interest	Unchanged
	Fossil energy resources and storage	No Information	No Information
	Geothermal resources	Poor resources as bedrock are at the surface and crustal thickness is very high	Unchanged
CULTURAL SERVICES	Historical, recreational, and sacred sites	There are some known and unknown cultural sites in the tunnel corridor	Assumed not to be affected as they lie at shallow depths
	Geo-scientific and Geo-educational resources	No geological heritage in the way of the tunnel corridor	No impact

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