Geosystem services from the subsurface: A literature review and a proposed set of indicators tailored to a Swedish setting

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Geosystem services from the subsurface: A literature review and a proposed set of indicators tailored to a Swedish setting

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ABSTRACT

In this study, a literature review was conducted to identify indicators that can be utilised to assess and visualise the potential of the geophysical environment to deliver geosystem services. The literature review identified 24 studies and 22 technical reports, resulting in a list of 75 geosystem services indicators for 23 geosystem services associated with the subsurface. Building upon these findings, a country-specific set of 21 indicators pertinent to the geological setting of Sweden was developed. Each developed indicator was further subdivided into different 'capacity classes' to denote the potential of the geophysical environment to deliver a specific geosystem service. Most of these proposed indicators can be directly applied (19 out of 21), as there is readily available information in open-access maps and databases. However, some of the assigned capacity classes need to be adjusted according to the spatial scale of application. Furthermore, to convey the benefit or value of a given geosystem service, the proposed indicators must also be complemented with estimates of accessibility and societal importance of said service. Nonetheless, the proposed set of indicators represents an initial step towards a comprehensive mapping of geosystem services that can be used to highlight the multitude of ways the subsurface contributes to society.

1. Introduction

1.1. Background

Ecosystem services are broadly recognised today in processes for decision-making, such as for spatial planning practices (e.g. Cornell, 2011; Daily and Ruckelshaus, 2022; Layke et al., 2012; Thorén & Stålhammar, 2018) and various types of impact assessments (Geneletti, 2016). Although frameworks such as CICES have recently included and expanded the list of ecosystem services covered (Haines-Young and Potschin-Young, 2018), several authors (e.g., Gray, 2018; van Ree et al., 2017) have noted that ecosystem services generally do not fully capture subsurface and abiotic services (recently labelled as geophysical services in CICES, Haines-Young, 2023). Similarly, geodiversity maps (based on geodiversity indices, see de Paula Silva et al., 2021; Pereira et al., 2013; Silva et al., 2013) created to raise awareness on the importance of

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geodiversity[1] (Gordon and Barron, 2013; Gordon et al., 2012; Gray et al., 2013) contain information regarding some of the services the subsurface can provide; however, these indices do not currently capture the full range of so-called geosystem services[2] (e.g. provisioning of underground space, subsurface habitats and geo-energy systems). There is, however, ongoing work to broaden the geodiversity taxonomy and link it to geosystem services (Hjort et al., 2024; van Ree et al., 2024), including suggestions of indicators specifically developed for subsurface resources and services, e.g. related to underground urban space (Bobylev, 2016) and geothermal resources (Cook et al., 2017). That said, a set of suitable indicators that describes the potential of the geophysical environment to deliver these geosystem services is currently lacking in the scientific literature.

The use of indicators (in a broad range of different sectors and disciplines) is a well-established method to highlight trends and characteristics of the represented system and to facilitate communication (Czúcz and Arany, 2016; Müller et al., 2016). The cascade model is a common way to illustrate the links between the physical environment and its benefits and values for humans (Czúcz et al., 2020; Haines-Young and Potschin-Young, 2018; Haines-Young and Potschin, 2012). It disentangles ecosystem services into a (bio)physical supply part (the environment) and a societal demand part (the social and economic system). This illustrates that a given environment holds certain potential to deliver a service that can fulfil societal needs and offer benefits (Albert et al., 2016; Andersson-Sköld et al., 2018; Burkhard et al., 2014; Potschin and Haines-Young, 2016). In continuation of this line of thought, a practical approach to indicator development is to separate the supply side (i.e. the physical environment) from the demand side (i.e. the social and economic system), rather than to use broad composite indicators. For example, Andersson-Sköld et al. (2018) and Czúcz et al. (2018) used the cascade model to derive indicators that specifically target the physical environment. The rationale for distinguishing the supply side from the demand side is to enhance applicability in routine planning processes by accommodating a broader range of perceived benefits and values, that may evolve over time, to be accounted for (e.g. due to a changing climate, enacted policies or laws, or shifts in perceived importance between different locations).

1.2. Aims and objectives

This study aims to arrive at a set of curated indicators[3] that can be used to assess and visualise the potential for delivering specific geosystem services related to the subsurface in a Swedish geological setting. A gross list of geosystem services related to the subsurface presented in Lundin-Frisk et al. (2022) and refined in Lundin-Frisk et al. (2024), was used to select relevant services. The gross list includes 39 geosystem services. The specific objectives of this study are: (1) to carry out a literature review to synthesise a list of indicators describing geosystem services, and (2) to suggest suitable indicators and 'capacity classes' for the study setting that capture the potential of a specific (geo)physical environment to deliver a specific geosystem service related to a specific use. The set of indicators compiled in this study provides a starting point for developing spatial maps of geosystem services, in this case limited to, and subsequently adapted to, a Swedish setting. Our set of indicators take climate and geological settings, as well as data availability, into consideration to facilitate nationwide spatial mapping of a multitude of underground resources.

2. Material and method

2.1. Area of study – Sweden

Sweden is situated in Northwestern Europe (Fig. 1). The Swedish landscape is varied, ranging from the Caledonian mountain range in northwestern Sweden to the low and flat areas of southern Sweden. The landscape of southern Sweden is predominantly agricultural, with increasing forest coverage northward. Around 65% of the landmass is covered by forest (boreal forests to the north and temperate deciduous forests to the south). The southern part of Sweden is characterised by a temperate continental climate with significant seasonal temperature differences, warm to hot (and often humid) summers and cold winters, whereas the north has a subarctic climate with long, cold winters, and short, warm to cool summers (Beck et al., 2018). Around 15% of Sweden lies north of the Arctic Circle. From a geological standpoint, Sweden is part of the Fennoscandian Shield, a tectonically stable segment of the East European Craton, characterised by a relatively young overburden, formed by numerous recent periods of glaciation and deglaciation during the Quaternary period (Stephens, 2020; Wastenson and Fredén, 2002). Details on the geological setting of Sweden are presented in the Supplementary Material (SM).

2.2. Identification of indicators from the literature

A systematic literature review using the Scopus database was carried out to synthesise a list of indicators for geosystem services related to the subsurface (Fig. 2). The search was limited to peer-reviewed geology, environmental science and engineering studies in English between 2000 and 2023. The search string contained the keywords 'abiotic ecosystem service', 'geodiversity', 'geosystem service', 'underground space', 'groundwater dependent ecosystem', 'underground construction', 'criteria', 'indicator' and 'mapping', as well as combinations of these words. Identified documents were screened by reading the abstracts and selecting studies that suggested one or more indicators for assessing geosystem services at a municipal, regional or national scale. The result of the search process was 24 articles that were deemed relevant to this study and thus included in the indicator synthesis (Fig. 2).

The search in Scopus was complemented by a review of indicators found in technical reports (so-called grey literature), including reports written by governmental agencies, municipalities, or consultants. This was done to fill gaps (i.e. if no indicator is found for a specific service) or to adapt indicators to the specific study setting (e.g. adaptation to specific lithological units). However, as there is no (global) searchable database for these types of sources, only general searches in the Swedish (https://www.sgu.se/en), Finnish (https://www.gtk.fi/en) and Norwegian (https://www.ngu.no/en) geological surveys' website databases were conducted, in conjunction with backward and forward reference searches of identified key reports. These databases were selected because they represent geological surveys that have conducted mapping of the Fennoscandian Shield and were thus presumed to contain information useful for adapting the identified indicators to the specific study context. This search resulted in 21 reports that contained descriptions of geophysical structures and processes that were relevant to our study. Each indicator identified from the scientific and grey literature was listed and described according to whether the indicator covers: (i) a part of the cascade model (i.e. 'geophysical environment'), or (ii) the full cascade model ('composite').

[1] Defined as 'the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform, processes) and soil features. It includes their assemblages, relationships, properties, interpretations and systems' (Gray, 2013, p. 8).

[2] Geosystem services refer to the contributions provided by the subsurface or abiotic nature (depending on the definition) to human well-being. It is an analogue to the more established ecosystem services. See the review by Lundin-Frisk et al. (2022) for more details. Geosystems services are typically sorted into four separate categories, following the Millennium Ecosystem Assessment classification of ecosystem services (Millennium Ecosystem Assessment, 2005): Regulating services; Supporting services; Provisioning services; and Cultural services.

[3] An indicator in this context refers to a simplified measure or information that communicates the characteristics and/or trends of the geophysical environment and the services it provides to humans.

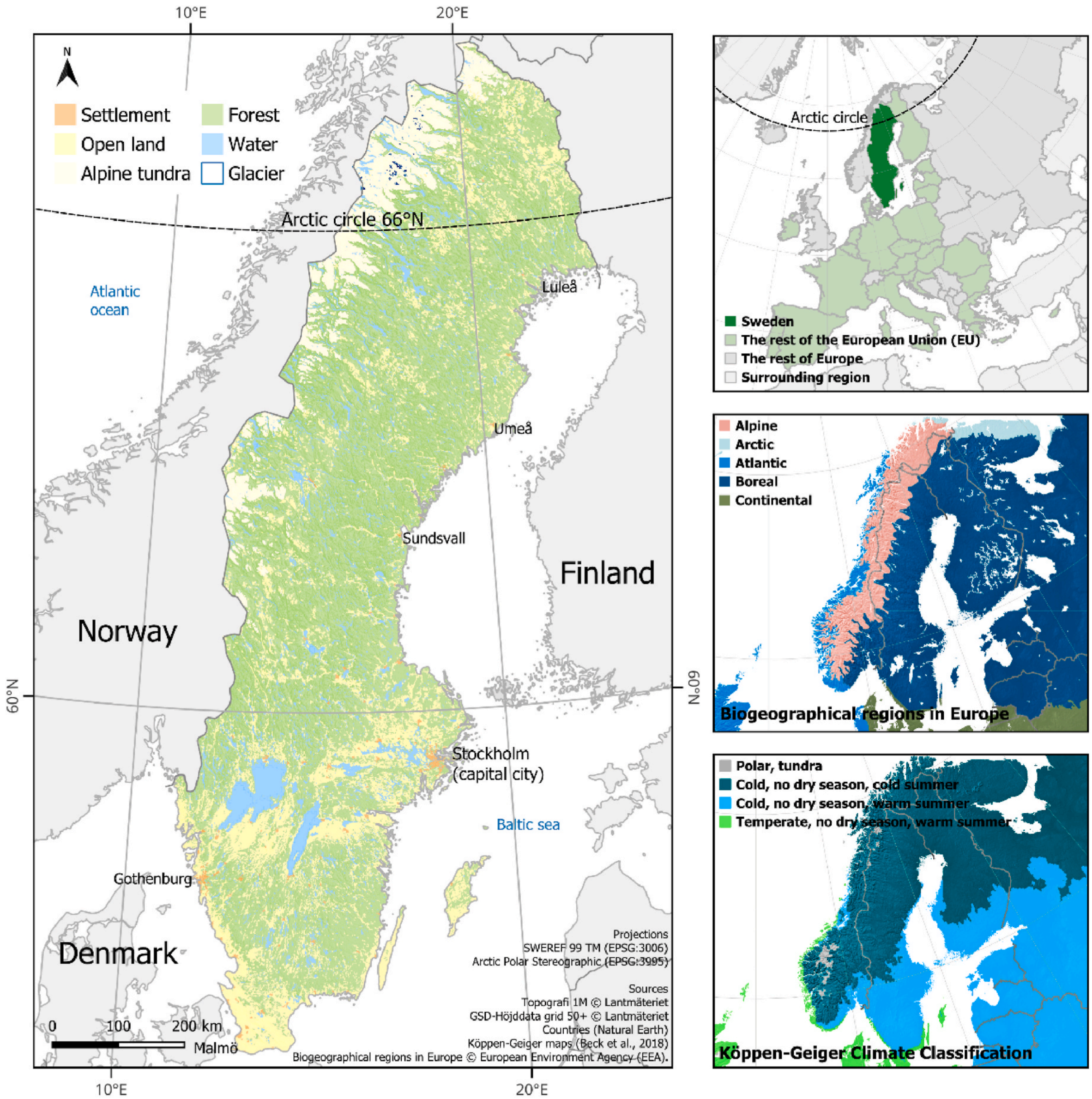

Fig. 1. Overview map of Sweden.|
Note: The Köppen-Geiger climate classification is based on the dataset from Beck et al. (2018). The biogeographical regions in Europe are based on the data set from the European Environment Agency (EEA) (see Roekaerts (2002)). For maps related to the geological setting of Sweden, see the SM.

2.3. Adaptation and development of indicators for Sweden

Based on the results of the literature review and the gross list of geosystem services related to the subsurface outlined in Lundin-Frisk et al. (2022, 2024), a curated set of indicators for the *potential* of the subsurface to deliver geosystem services was developed. These indicators are targeted at the geophysical supply part, i.e. indicators that cover the first three parts of the cascade model or 'geophysical environment' (Fig. 3). The geophysical supply component contributes to delivering a given service, either directly (e.g. permeable soil[4] that can be used to infiltrate stormwater to reduce risk of flooding) or indirectly (e.g. subterranean fauna species' variation that can increase the potential for supply of subsequent services provided by said species). Consequently, Regulating, Supporting, Provisioning, and Cultural services are all included in the curated list of services, given that what constitutes a final service in itself can be contingent on the specific context (see e.g., Lundin-Frisk et al., 2024). However, indicators that encompass both the potential of the geophysical environment to deliver services, the benefits these services confer, and the demand for said services are regarded as composite indicators and thus, were not selected for further adaptation to the study setting.

The indicators found in the literature that indicate the potential to deliver a specific service (the geophysical environment) were examined to determine their applicability in the specific geological setting found in the study area, including considerations of data availability. If they were deemed unsuitable, or for those geosystem services where no indicator was identified, new indicators were suggested by the authors. The developed indicators proposed in this study are, thus, either adaptations of indicators identified in the literature review to better suit the study area or indicators suggested by the authors. For each geosystem service (and subsequent utilisation) for which more than one indicator was

[4] The term 'soil' has different connotations in various subject areas. In this study, soil refers to 'a mostly unconsolidated assemblage of particles that are affected by physical, chemical, and/or biological processes at or near the planetary surface'.

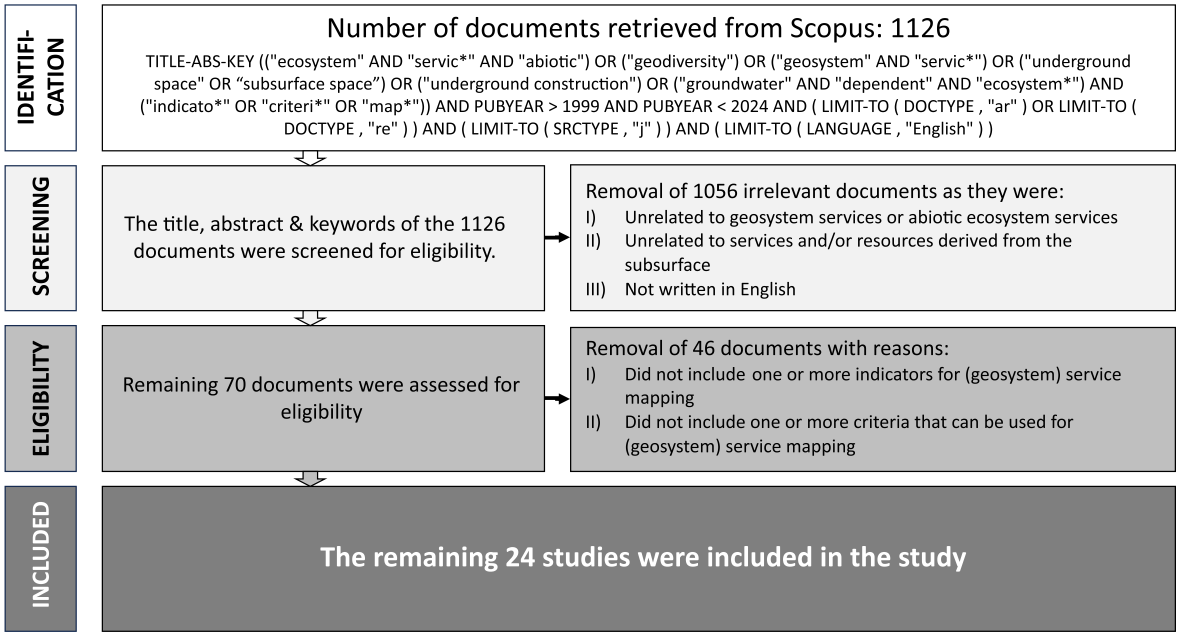

Fig. 2. PRISMA flow diagram showing an overview of the search process and its results. The literature review includes publications up to June 10th' 2023.

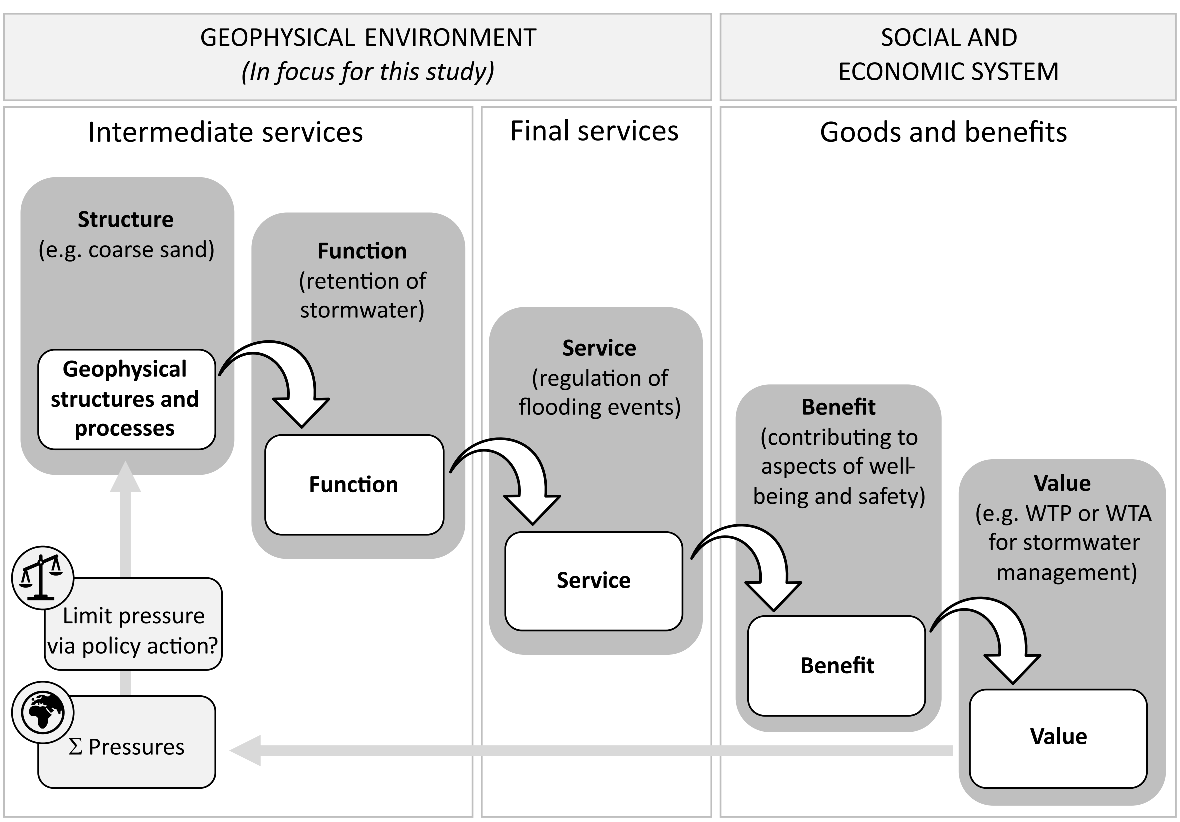

Fig. 3. The cascade model after Haines-Young and Potschin (2010), adapted to illustrate geosystem services (Haines-Young, R., 2023; van Ree and van Beukering, 2016).
Notes: In the adapted and modified cascade model, 'biophysical structures and processes' are replaced by 'geophysical processes and structures' and 'environment' by 'geophysical environment'. Coarse-grained sand, with its ability to retain stormwater, is used as an example to illustrate the cascade of geophysical structures and processes, functions, services, benefits and values of the geosystem service 'regulation of flooding events'. The 'geophysical environment' refers to the structures and processes that could facilitate a potential supply of a given service, whereas the 'social and economic system' refers to the demand of said service. WTP = willingness to pay, WTA = willingness to accept compensation.

deemed suitable, the indicator with the most available data was selected for further adaptation. The adapted indicators were also specified in greater detail to explicitly connect each indicator to a specific service and use. This approach was necessary as each individual geosystem service is inherently broad and can encompass many different types of uses that provide different benefits, and thus, may require different indicators related to each specific use.

To indicate whether a certain indicator, or a specific value range of a measurable quantity used as an indicator, is associated with a high or low potential to deliver a specific service, a capacity class was assigned to each indicator. Each capacity class is a simplistic estimation of the potential to deliver a given geosystem service and is dependent on the setting and scale of the application. Class A implies high potential, class B implies some potential, class C implies low potential and class D implies no, or very limited, potential. For this study, a Swedish setting (including e.g. climate, geology and geomorphology) and a national scale are used. Please note that in this context, 'capacity classes' solely describe the potential to deliver a specific service, without considering the suitability of utilising said service or its accessibility.

Assigning a capacity class to each geosystem service indicator follows the methodology used by Andersson-Sköld et al. (2018) to assess the benefits and values provided by urban greenery. Following the cascade model, they combined the abundance of indicators related to biophysical structures and processes with an effectiveness factor to determine the potential for delivering each ecosystem service investigated. In Andersson-Sköld et al. (2018), this potential is combined with an estimation of the benefit of each ecosystem service to derive a total ecosystem service value. Their method can thus be considered to consist of two parts: (1) indicators representing the biophysical environment which are used to measure structures and processes and that have different potentials to provide ecosystem services, representing the biophysical environment, and (2) assigned importance or value of each service, representing the social and economic system (Fig. 3). Similar point systems of effectiveness but related to geological and geomorphological features can be found in for example Bathrellos et al. (2012) and Depountis (2023). This study covers the first step (i.e. indication of potential) of the methodology developed by Andersson-Sköld et al. (2018) but focuses on geosystem services.

The identification of the most relevant indicators from the literature, the adaptation of some of them and the development of new ones, as well as the classification of the capacity of all these indicators, were based on internal discussions within the project group and input from one external expert at the Research Institute of Sweden (RISE). Only beneficial processes and structures were considered. Processes that are disadvantageous, referred to as risks or disservices (von Döhren and Haase, 2015), such as, for example, the formation of radon from uranium-bearing rocks, were not included in this study. While essential for spatial planning, risks or disservices were excluded from our study for two reasons: (1) it is counterintuitive to include them from a service perspective (i.e. the direct and indirect contributions to society and human welfare), and (2) there are already well-established databases and maps for many of these risks (e.g., SGI, 2023). It should be noted that the indicators discussed in this study are by necessity simplifications of complex structures and processes. These simplifications are necessary to fit the study scale, data availability and modelling/mapping feasibility. All suggested indicators, adaptations and developments, the information used in this study, as well as the availability of data related to the suggested indicators, can be found in the Supplementary Materials (SM).

3. Results and discussion

3.1. Identification and compilation of indicators from the literature

After the screening, 24 studies and 22 technical reports provided a list of 75 geosystem services indicators for 23 different geosystem services systematised into sections of regulating, supporting, provisional or cultural services. The list of indicators for each individual geosystem service is presented in Table 1. The notes in Table 1 also include information on (1) type of literature it was sourced from, (2) whether it was deemed to focus on the geophysical environment or if it is more of a composite indicator, (3) whether it focuses on benefits, disservices, or both, and (4) whether said indicator was subsequently selected for further adaptation to the specific study setting. For convenience, as these 75 indicators overlap to some extent, i.e. cover multiple services, a list of all unique indicators (53 in total) is also presented in Table 1A in the Appendix.

3.1.1. Indicators in the scientific literature

The indicators identified in the scientific literature span a wide range of methods (Table 1), including direct measurements (such as microorganisms and invertebrates), proxies (such as the number of different genes measured in water samples), indices (such as the Water Retention Index [WRI]) and composite indicators (such as the quantity of raw material produced). Most indicators aim to evaluate 'abiotic ecosystem services' or geodiversity and geoheritage. Only two articles, Finesso and Van Ree (2022) and Tognetto et al. (2021), specifically mention geosystem services. Most studies refer to the provisioning section (43%) and the regulating section (29%) of services. These sections cover a wide range of services that often also have a well-established value (e.g. extraction of metals and groundwater, flooding and landslide mitigation). While supporting services are contentious within ecosystem services frameworks such as CICES (e.g. Jax, 2016; Potschin and Haines-Young, 2016), 7% of the indicators found during our literature review relate to such supporting geosystem services (habitat provisioning and groundwater dependent ecosystems). For the services regulation of temperature by the subsurface, regulation of soil and bedrock chemistry and disposal and storage (CCS),[5] no indicators were found in the scientific literature.

Common types of indicators found are average production or provisioning of something (such as total kg/year or litre/hour), different indices (such as 'landscape index, Water Retention Index, Value Index) and geodiversity indices (such as mineral resource diversity index). Geodiversity indices are especially common for provisioning services, given the difficulty of directly assessing the spatial distribution of provisioning services (such as geomaterials), closeness to a known resource is used as an indicator for these services (Silva et al., 2013). In addition, composite indicators, such as the average production of a given material (Grima et al., 2023), are commonly used in provisioning services.

Of the indicators identified in the review, 46% relate mainly to either structures or functions (describing the geophysical environment), whereas the remaining 54% can be viewed as composite indicators (Table 1). Indicators for regulating and supporting services tend to refer to the geophysical environment, whereas composite indicators are more common for provisioning and cultural services. The indicators highlighted in the review for the three services of regulation of erosion, mass movements and soil and bedrock chemistry relate mainly to disservices or risks (e.g., health risks due to radon and acidification due to sulphide-bearing rocks) rather than indicating a potential service (Table 1). While some tendencies to indicate risks rather than potentials are also seen in the regulating services regulation of water quantity and regulation of stress and strain, these tendencies are more prominent for the three services listed previously (regulation of erosion, mass movements and soil and bedrock chemistry).

3.1.2. Indicators in technical reports

None of the technical reports in the review specifically refer to

[5] Underground space for disposal and storage refers to storage in the pores of natural formations (e.g. sandstone). For storage in constructed spaces, see provisioning of underground space.

Table 1
A synthesised list of indicators for geosystem services.

Section	Geosystem service	Indicator [suggested units]	Source	Notes			
Regulating services	Regulation of erosion	Soil eroded [kg, $ml^{-2}h^{-1}$]	Czúcz et al. (2018)			−	-
		Landscape index [-] *	Czúcz et al. (2018)			±	-
		Soil erodibility [-] *	Mallinis et al. (2023)			−	-
			SGI (2023)			−	-
	Regulation of mass movements	Landscape index [-] *	Czúcz et al. (2018)			±	-
		Slope stability ratio [-] *	Grima et al. (2023) referring to (Band et al., 2012)			±	-
		Quantity of mass flows regulated [n]	Haines-Young and Potschin-Young (2018)			−	-
		Soil eroded [kg, $ml^{-2}t^{-1}$]	Czúcz et al. (2018)			−	-
		Soil instability [-] *	SGI (2023)			−	-
	Regulation of water quantity	Reduced flood risk area [m^2, $m^2person^{-1}$]	Czúcz et al. (2018)			+	-
		Storage and permeability capacity [-] *	Czúcz et al. (2018)			+	-
		Quantity of water filtered [l^3/h]	Grima et al. (2023); Haines-Young and Potschin-Young (2018)			+	-
		Water Retention Index (WRI) composed of sub-indicators [-] *	Grima et al. (2023); Vandecasteele et al. (2018)			+	-
		Permeability index [-] *	Carlsson et al. (2020); Lewis et al. (2006)			+	(✓)
	Regulation of water quality	Quantity of water filtered [l^3/h]	Grima et al. (2023) referring to Laterra et al. (2012)			+	-
		Biochemical degradation capacity [-] *	Grima et al. (2023) referring to Böhnke-Henrichs et al. (2013)			+	-
	Regulation of temperature by the subsurface	Thermal conductivity (λ) [W/(K m)]	Erlström et al. (2016)			+	✓
	Regulation of soil and bedrock chemistry	Gamma-ray radiation [eU ppm]	Jelinek and Eliasson (2015)			−	-
		Sulphur content [mg/kg]	Trafikverket (2015)			−	-
	Regulation of stress and strain	Soft ground thickness [m]	Peng and Peng (2018)			±	(✓)
		Soil uniformity [-] *	Peng and Peng (2018)			±	-
		Lineament density (e.g., faults, fracture zones, etc) [m/m^2]	Peng and Peng (2018)			±	(✓)
		Terrain classes [-] *	SGI (2016)			+	✓
Supporting services	Habitat provision (stygofauna and troglofauna)	Number of genes [-]	Steube et al. (2009)			+	-
		Legal protection [-] *	Tognetto et al. (2021)			+	-
		Number of symbolic species [-]	Steube et al. (2009)			+	-
		Dissolved oxygen [mg l^{1}]	EPA (2016); Thulin & Hahn (2008)			+	-
		Electric conductivity [μS cm^{-1}]	EPA (2016); Thulin & Hahn (2008)			±	-
		Hydrogeological units* [-]	EPA (2016)			+	✓
		pH [-]	EPA (2016); Thulin & Hahn (2008)			±	-
	Groundwater dependent ecosystems	Indexes composed by sub-indicators (e.g., lithology, groundwater level, photosynthetic activity, wetlands, etc) [-] *	Cruz et al. (2022); Duran-Llacer et al. (2022); El-Hokayem et al. (2023); Fildes et al. (2023); Gou et al. (2015); Link et al. (2023); Münch and Conrad (2007); Pandey et al. (2023)			+	-
		Symbolic species [n]	Thorsbrink et al. (2016); Söderqvist et al. (2014)			+	✓
Provisioning services	Disposal and storage (CCS)	Deep saline aquifers [-]	Møl Mortensen and Sopher (2021) Teir et al. (2010)			+	-
	Underground space	Developed underground space [m^3]	Bobylev (2016); Finesso and Van Ree (2022); Peng and Peng (2018)			±	-
		Developed underground space per person [m^3/person]	Bobylev (2016); Finesso and Van Ree (2022)			±	-
		Underground premises floor area [m^2]	Bobylev (2016)			±	-
		Urban underground infrastructure density (UUID) [m^3/m^2]	Bobylev (2016); Finesso and Van Ree (2022)			±	(✓)
		Developed surface space [m^3]	Peng and Peng (2018)			−	-
	Groundwater for drinking	Groundwater level [m]	Czúcz et al. (2018)			±	-
		Current groundwater extraction [l^3/h]	Grima et al. (2023) Thorsbrink et al. (2014)			±	-
		Number of springs [n]	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)			+	-
		Potential extraction capacity [l^3/h]	Grima et al. (2023); Haines-Young and Potschin-Young (2018) Hjerne et al. (2021b)			+	✓
		Hydraulic conductivity in rocks [$log_{10}(K)$]	Hjerne et al. (2021a)			+	-
		Number of wells [n];	Czúcz et al. (2018) Thorsbrink et al. (2014)			+	-
	Groundwater used as a material	Groundwater level [m]	Czúcz et al. (2018)			±	-
		Current groundwater extraction [l^3/h]	Grima et al. (2023) Thorsbrink et al. (2014)			±	-
		Number of springs [n]	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)			+	-
		Potential extraction capacity [l^3/h]	Grima et al. (2023); Haines-Young and Potschin-Young (2018) Hjerne et al. (2021b)			+	✓
		Hydraulic conductivity in rocks [$log_{10}(K)$]	Hjerne et al. (2021a)			+	-
	Minerals for nutritional purposes	Quantity of salt produced [kg]	Grima et al. (2023); Haines-Young and Potschin-Young (2018)			+	-
	Non-renewable energy resources	Mineral resource diversity index [-]	Ahmadi et al. (2021); de Paula Silva et al. (2021); Pereira et al. (2013); Silva et al. (2013)			+	-
		Fossil fuel extracted [kg]	Grima et al. (2023); Haines-Young and Potschin-Young (2018)			±	-
	Geothermal resources	Potential geothermal power capacity [-]	Grima et al. (2023) referring to Cook et al. (2017)			+	-
		Geothermal gradient or heat-flow [°C /km or mW/m^2]	Duffield and Sass (2003)			+	✓
	Construction materials	Quantity of raw materials produced [kg]	Grima et al. (2023); Haines-Young and Potschin-Young (2018)			±	-
		Metallogenic belt [-] *	Eilu (2012)			+	✓
		Lithological units [-]	Mortensen et al (2023)			+	✓
	Industrial minerals	Quantity of minerals produced [kg]	Grima et al. (2023); Haines-Young and Potschin-Young (2018)			±	-
		Mineral resource diversity index [-]	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)			+	-
		Metallogenic belt [-] *	Eilu (2012)			+	✓
	Metallogenic resources	Quantity of minerals produced [kg]	Grima et al. (2023); Haines-Young and Potschin-Young (2018)			±	-
		Mineral resource diversity index [-]	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)			+	-
		Metallogenic belt [-] *	Eilu (2012)			+	✓
	Ornamental resources	Mineral resource diversity index [-]	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)			+	-

Cultural services	Iconic sites (e.g. caves for exploration and tourism)	Aesthetic Value Index [-]	Grima et al. (2023) referring to Sherrouse et al. (2011)	black and white literature	geophysical	+	-
		Employment [-]	Czúcz et al. (2018)	black and white literature	composite	+	-
		Number of enterprises [n]	Czúcz et al. (2018)	black and white literature	composite	±	-
		Geotopes [-] *	Fassoulas et al. (2012) Lundqvist and Dahl (2020)	black and white literature grey literature	geophysical	+	✓
		Geoparks [-]	Tognetto et al. (2021) Schoning and Lundqvist (2020)	black and white literature grey literature	composite	+	✓
		Number of symbolic species [n]	Grima et al. (2023)	black and white literature	geophysical	+	-
		Number of visitors [n]	Fox et al. (2022); Grima et al. (2023); Haines-Young and Potschin-Young (2018); Stanley et al. (2023)	black and white literature	composite	±	-
		Geosite [-]	Schoning and Lundqvist (2020)	grey literature	geophysical	+	✓
	Sacred and historical sites	Number of visitors [n]	Czúcz et al. (2018); Haines-Young and Potschin-Young (2018)	black and white literature	composite	±	-
		Number of people participating in sacred activities [n]	Grima et al. (2023); Haines-Young and Potschin-Young (2018)	black and white literature	composite	+	-
	Scientific and educational resources	Geotopes [-] *	Fassoulas et al. (2012) Schoning and Lundqvist (2020)	black and white literature grey literature	geophysical	+	✓
		Geoparks [-]	Tognetto et al. (2021)	black and white literature	composite	+	✓
		Time spent [h]	Grima et al. (2023)	black and white literature	composite	+	-
		Geosite [-]	Schoning and Lundqvist (2020)	grey literature	geophysical	+	✓

Key to table: Indicators sourced from scientific literature are marked with (black and white literature icon, 'black and white literature') whereas indicators sourced from technical reports are marked with (grey literature icon, 'grey literature'). Indicators that are deemed by the authors to focus on the geophysical environment are marked with (geophysical icon), whereas composite indicators that include both the potential and demand of said service are marked with (composite icon). Indicators that focus on benefits are marked with (+), whereas those that focus on disservices or risks are marked with (−). Indicators that include aspects of both benefits and disservices or risks are marked with (±). Indicators marked with ✓ (without modification) or with ✓ within parentheses (with modification), were selected for further adaptation to the specific study setting. See section 3.2 for reasoning behind the selection of indicators for further adaptation, and for a list of publications identified in the literature review, see Appendix. For a description of the suggested units, please see the referenced literature. The * marks a qualitative description.

geosystem services. They do, however, provide descriptions of how generic geological units (e.g. granite, gabbro), formations (e.g. ridges, eskers) or specific measurements (e.g. hydraulic conductivity in rocks) can be used to spatially map specific resources. These descriptions were used to infer potential indicators for geosystem services.

The reports contained two inferred indicators (for the services: 'regulation of temperature by the subsurface'; 'disposal and storage') that can be used to fill gaps left by the scientific literature (Table 1). An additional eight inferred indicators were used to adapt 12 of the suggested indicators in the scientific literature (Table 1) to the specific study setting (see section 5.2 for suggested adaptations). In contrast to the indicators identified in the scientific literature, these inferred indicators mainly relate to structures and processes of the geological stratum (as compared to the composite indicators suggested for provisioning and cultural services in scientific literature). They were also used to delimit the included services in this study, as not all services are relevant for this specific study setting. The study area lacks sources of non-renewable energy resources (with the exception of uranium, see e.g. Erlström, 2014) and minerals that can be used directly for nutritional purposes (e.g. salt) that are presently economically viable for extraction. However, from a historical perspective, both non-renewable energy resources (e.g. peat, lignite, coal and bituminous shale) and minerals for nutritional purposes have been extracted. As an example, during World War II, bituminous shale (alum shale) was an important source of domestic petroleum production.

3.2. *Adaptation of the selected indicators to the specific study setting*

Using the results of the literature review as a basis, we developed and assigned capacity classes to indicators suitable for the study setting. The capacity classes capture the potential of the geophysical environment to deliver a specific service (i.e. estimates on the potential to deliver a specific service). Indicators for regulating services are described in section 3.2.1, summarised in Table 2, with more detailed information available in Tables S1–S8 in the SM; supporting services in section 3.2.2, Table 3, and Tables S9 and S10; provisioning services in section 3.2.3, Table 4, and Tables S11–S17; and cultural services in section 3.2.4, Table 5, Tables S18 and S19. The detailed information in the SM (Tables S1–S19) expands on the descriptions in the following sections. The SM also includes information on the availability of Swedish and Nordic open-access databases and maps, which contain information on these indicators.

3.2.1. *Regulating services*

The section on regulating services encompass five specific services: (1) suitable construction conditions in the subsurface, (2) suitable construction conditions on the surface, (3) retention, (4) filtration of stormwater and (5) extraction of heat or cold from shallow geo-energy systems. Of the indicators highlighted in the literature review that relate to regulating services (Table 1), three indicators highlighted were used without modification ('terrain classes', 'permeable soils' and 'thermal conductivity'); three indicators were modified to fit the study setting ('rocky type', 'lineament density' and 'soft ground thickness'); and one was suggested by the authors ('permeable and reactive soils') (Table 2). The indicators identified in the review for the services 'regulation of erosion', 'mass movements', and 'soil and bedrock chemistry' are not included in the curated list, as they relate mainly to risks rather than potentials.

3.2.1.1. Indicators for regulation of stress and strain. Regulation of stress and strain refers to the ability of the subsurface to distribute loads to create a stable medium to build on top of or within. To select and develop suitable indicators, regulation of stress and strain is divided into two more specific geosystem services: (1)) the ability to regulate stress and strain in underground constructions, and (2) the ability to distribute stress and strain as a result of surface load.

3.2.1.1.1. Indicators for suitable construction conditions in the subsurface. Subsurface constructions, like tunnels and caverns, depend on the ability of the surrounding geological material to distribute stress and strain. The need for reinforcement of the construction depends on the material itself, its structures (i.e. fracture systems) and the thickness of the rock cover. The Swedish bedrock is, in general, composed of rocks that possess a high ability to withstand applied loads without failure or plastic deformation. Capacity class A is suggested as standard for most of the crystalline bedrock and class B for layered or stratified bedrock (see Table S1 in the SM). Challenges for underground construction in the Swedish bedrock are rather related to the rock cover thickness, the frequency of fractures[6] and their orientation and properties, as well as

[6] A fracture in this context refers to any separation of the geologic formation, such as a joint or a fault that divides the rock.

Table 2
Geophysical components contributing to the regulation of geosystem services, related functions, indicators and assigned capacity class.

Geosystem service	Specific service	Specific use	Function	Indicator	Suggested capacity classes for a Swedish setting		Reference(s)
Regulation of stress and strain	Suitable construction conditions in the subsurface	Use of the subsurface as a construction medium	Ability of the bedrock to distribute stress and strain around tunnels and caverns	Rock type [-]	Massive rock units	A	Inferred from Peng and Peng (2018), modified after authors' own suggestion. **See** Tables S1, S2 & S3 **in the SM.**
					Layered or stratified rock units	B	
				Lineament density [n]	Proximity to/or intersecting lineaments	C	
				Soft ground thickness [m]	<10 m	A	
					10–30 m	B	
					>30 m	C	
	Suitable construction conditions at the surface	Use of the subsurface as a stable platform or foundation	Ability of the terrain to distribute stress and strain as a result of surface load	Terrain classes [-]	Stable terrain classes	A	SGI (2016). **See** Table S4 in the SM.
					Unstable terrain classes	C	
Regulation of groundwater quantity	Retention of stormwater	Use of the subsurface for infiltration and storage of water to reduce flooding	Ability to infiltrate and store stormwater	Permeable soils [-]	Exceptional permeability	A	Carlsson et al. (2020); Lewis et al. (2006). **See** Table S5 in the SM.
					Good permeability	B	
					Poor permeability	C	
Regulation of groundwater quality	Filtration of stormwater	Use of the subsurface to improve stormwater quality and reduce the cost of water treatment	Ability to filter and adsorb substances and particles from stormwater	Permeable and reactive soils [-]	Exceptional reactivity	A	Authors' own suggestion. **See** Table S6 in the SM.
					Good reactivity	B	
					Poor reactivity	C	
Regulation of temperature by the subsurface	Extraction of heat or cold from shallow [<400 m] geo-energy systems with drilled wells	Use of the subsurface to extract and store heat or cold	Ability to store and transfer heat and cold	Thermal conductivity, λ [W/(K m)]	>4,5 W/(K m)	A	Erlström et al. (2016). **See** Tables S7 and S8 in the SM.
					2.5 - 4,5 W/(K m)	B	
					<2.5 W/(K m)	C	

Note: Sources are presented when available. If no suitable indicator was identified from the literature review, an indicator is suggested based on internal project team discussions. Class A – implies high potential, class B – implies some potential, class C – implies low potential, and class D – implies no or a limited potential. Suggested capacity classes are developed for a Swedish setting. SM = Supplementary Material.

Table 3
Geophysical components contributing to supporting geosystem services, related functions, indicators and assigned capacity class.

Geosystem service	Specific service	Specific use	Function	Indicator	Suggested capacity classes for a Swedish setting		Reference(s)
Habitat provision	Providing habitats for wild subsurface organisms that support biodiversity	Provisioning of ecological conditions for sustaining populations of stygofauna and troglofauna that people use or enjoy	Geological and hydrological structures and processes govern the availability of suitable micro-habitats for subterranean fauna	Lithological units (subterranean habitats)	Karst, glaciofluvial, alluvial & colluvium formations	A	EPA (2016); Thulin and Hahn (2008). **See** Table S9 in the SM.
					Weathered and/or fractured sandstone or limestone	B	
Groundwater dependent ecosystems	Providing habitats for wild surface organisms that support biodiversity	Provisioning of ecological conditions for sustaining populations of species that people use or enjoy	The subsurface governs the availability of groundwater that some ecosystems depend on	Surface habitats	Very high preservation value	A	Thorsbrink et al. (2016). **See** Table S10 in the SM.
					High preservation value	B	

Note: Sources are presented when available. If no suitable indicator was identified from the literature review, an indicator is suggested based on internal project team discussions. Class A – implies high potential, class B – implies some potential, class C – implies low potential, and class D – implies no or a limited potential. Suggested capacity classes are developed for a Swedish setting. SM = Supplementary Material.

the groundwater pressure head. At a site-specific scale, there are several rock classification systems, where the Q-system introduced by Barton et al. (1974) and rock mass rating (RMR) proposed by Bieniawski (1989) are two common examples. That said, the use of these rock classification systems on a larger scale is limited by data availability. Information related to the subsurface is typically found in various databases and in different formats, often linked to completed or ongoing infrastructure and construction projects. Until more detailed information on the subsurface is available, regional bedrock maps with lineaments could be used to identify areas where there is a lower subsurface capacity to distribute stress and strain.

We suggest that the presence of a lineament can be used as an indicator, and an area within 50 m of a lineament is given a capacity class C (see Table S2 in the SM). Another approach, which can be combined with type of bedrock and fracture frequency, is to use soil depth data. If the soil depth is great, underground constructions need to be placed at greater depths or thin rock cover might need to be accounted for. If the rock cover is thin, the bedrock beneath might not be self-supporting (due to low horizontal forces compared to the vertical load), which can require additional reinforcement (increasing construction costs and/or causing safety concerns). When using soil depth as an indicator of the ability to regulate stress and strain, the following capacity classes are suggested: a soil depth <10 m is given a capacity class A, >30 m a capacity class C, and for 10 m < soil depth <30 m a capacity class B is assigned (see Table S3 in the SM).

3.2.1.1.2. Indicators for suitable construction conditions on the surface. For surface constructions, the stability of the ground is of paramount importance, both from a safety and an economic perspective. Although there is an extensive body of literature on geotechnical aspects relating to construction (e.g. Chaminé et al., 2021; Viggiani and de Sanctis, 2009), less information is available regarding useful indicators for assessing the potential for construction at a regional or larger scale. Geotechnical terrain classification has been suggested for Sweden as a spatial planning tool that can be used in comprehensive planning (SGI, 1984, 2016, 2017). This geotechnical classification system assumes that sections of terrain that share topographical, geological and hydrogeological features have similar geotechnical properties (SGI, 1984). Hence, geotechnical terrains can be used to indicate the inherent potential for construction in given area. The studies by the Swedish Geotechnical Institute (SGI, 2016, 2017) suggest a sorting of the prevalent soil types in Sweden into stable and unstable terrains (see Table S4 in the SM). The stable terrains are assigned the capacity class A and thus have a low expected cost associated with construction, whereas the unstable terrains are less suitable for construction and are assigned the capacity class C.

3.2.1.2. Indicators for regulation of water quantity (retention of stormwater). Regulation of water quantity refers to the capacity of the ground for infiltration, percolation, and storing and transmitting water. The potential of the subsurface to regulate water quantity is influenced by various factors: precipitation, temperature, soil type, vegetation, topography and geology. The ability of the subsurface to store and transmit water has broad applications, it is, for example, important for artificial groundwater recharge and stormwater retention in the built environment. The indicator adapted in this study refers to the specific use of retaining stormwater. There are several indicators related to the retention of stormwater in the reviewed scientific literature (see Table 1). These range from 'reduced flood risk area' (Czúcz et al., 2018), to 'quantity of water filtered' (Grima et al., 2023), to permeability indices (Carlsson et al., 2020; Lewis et al., 2006). Of the indicators proposed, the permeability indices have the greatest data availability. Thus, two indices identified in the reviewed literature were selected for further adaptation to the study setting.

Lewis et al. (2006) developed a permeability index to provide a qualitative classification of vertical flow rates through the unsaturated zone based on the type of lithology and predominant flow mechanism (via fractures, intergranular or mixed). Carlsson et al. (2020) use another permeability index based on generalised soil lithologies in their tool Ekogeokalkyl. Both permeability indices can be used to estimate the ability of the subsurface to absorb and retain water (assessed through potential vertical fluid movement velocity) and are generally adaptable to the study scale (see Table S5 in the SM for assessments of common soil types). Hence, a combination of the two indices is proposed to indicate the potential of said service. That said, to capture the full relative capacity of the environment to regulate water, an index which combines the effects of both ecosystem and geosystem services should be used. The Water Retention Index (WRI) proposed by Vandecasteele et al. (2018) is such an index and includes interception by vegetation, storage in surface water bodies, as well as infiltration and retention in soils and aquifers. Also, to increase accuracy, other parameters, such as soil depth, slope and soil sealing, can be added to the proposed indicator and/or more advanced computer-based models such as Mike SHE (see e.g. Xevi et al., 1997) and SWMM (see e.g. Niazi et al., 2017) can be used.

3.2.1.3. Indicators for regulation of water quality. The water chemistry in both percolating water in the unsaturated zone, as well as in the groundwater zone, is affected by interaction with the soil or rock minerals and organic matter. Important processes include weathering, ion exchange, carbonate reactions, sorption, decay of organic matter, dissolution and precipitation. These processes are governed by the physical structure of the geological material, mineralogy, temperature, pressure, acid-base conditions, redox conditions, presence and state of organic matter and by the hydrochemical conditions of the water. As pollutants carried by the water are immobilised, diluted or transformed[7] by the geological strata, the water quality is regulated. One indicator suggested in the reviewed literature is to estimate the 'quantity of water filtered' based on soil type, wetland and vegetation cover. However, the focus is on wetlands and associated biophysical structures and processes (Laterra et al., 2012), thus referring largely to ecosystem services. In order to include the geophysical aspects contributing to said service, the adapted indicator focuses on the ability of the subsurface and the geological stratum to filter and adsorb substances and particles from infiltrating water to ensure that the underlying groundwater is not compromised (i.e. reducing the need and cost of treatment of extracted groundwater). The ability of the subsurface to regulate the quality of percolating water (i.e. water above the groundwater level) is in general terms controlled by the permeability and the thickness of the unsaturated zone and the reactivity of the soil. For the specific study scale, an index (filtration capacity) of likely water-sediment interactions and turn-over time of percolating water for generic soil types could be used to estimate the potential of different geological strata to regulate the quality of percolating water. For a detailed list of common soil types and their estimated filtration capacity, see Table S6 in the SM.

3.2.1.4. Indicators for regulation of temperature (extraction of heat or cold in shallow [<400 m] geo-energy systems with drilled wells). The subsurface can store and transfer heat and cold, which can be used for geo-energy. Geo-energy refers to the use of energy stored in soil, rock and groundwater to heat, or cool, buildings. Low-temperature geo-energy systems are either passive systems that rely on the sun to recharge energy into the subsurface, or active systems that are used to periodically store excess heat or cold in the uppermost part of the earth's crust (<400m depth) for extraction when needed (Erlström et al., 2016). There are several different types of geo-energy systems, such as horizontal ground heat exchangers and open ground water loop systems. In this study we have specifically focused on borehole heat exchangers (BTES). The potential for borehole heat exchangers in Sweden is generally quite good due to the relatively thin soil cover (see geological description in the SM). However, only one study in the reviewed literature referred to shallow geo-energy systems (Table 1).

The possible energy storage and output from a drilled energy well is influenced by groundwater flow, the surrounding rock temperature and rock properties. There are mainly two rock properties that are of interest: specific heat capacity and thermal conductivity (λ). The Geological Survey of Sweden (SGU) suggested using thermal conductivity as the sole indicator of geo-energy potential, i.e. an indicator expressing the capacity for energy extraction in long-term steady-state conditions (Erlström et al., 2016). The total bulk thermal conductivity is governed by the mineralogical composition and physical properties, such as porosity and permeability, of the rock (see Table S8 in the SM for a list of the thermal conductivity of common rocks and soils). Although the Swedish bedrock is generally well suited for geo-energy wells, some rock types perform better than others. The SGU has developed a nationwide geo-energy map based on estimates of the thermal conductivity which are calculated theoretically by using information about the mineralogical composition of the rock (Horai and Baldridge, 1972). Inferred from Erlström et al. (2016), the suggested capacity classes (see Table 3) are:

[7] Geosystem services in this context refer to beneficial processes. However, groundwater can also contain pollutants due to natural processes within the geological stratum, e.g. arsenic released in groundwater, such as in the Bengal Delta (Bhowmick et al., 2018).

class C for λ < 2.5, class B for λ 2.5–4.5, and class A for λ > 4.5 (see Table S7 for a list of the categories and related λ values suggested by Erlström et al., 2016). Ideally, additional indicators that can capture the potential for other types of shallow geo-energy systems, such as for Aquifer Thermal Energy Storage (ATES) or horizontal ground source heat pumps, should be developed.

3.2.2. Supporting services

The section on supporting services encompasses two specific geosystem services: (1) habitat provisioning for subterranean organisms by the subsurface and (2) provisioning of groundwater to dependent ecosystems. Of the indicators related to supporting services highlighted in the literature review (Table 1), two indicators ('lithological units' and 'surface habitats') are proposed without modification (Table 3).

3.2.2.1. Indicators for habitat provision (for stygo- and troglofauna). Habitat provisioning refers to the ability or the potential of the subsurface to provide suitable habitats for a wide range of subterranean species (see e.g. Guzik et al., 2011; Ivarsson et al., 2018; Reisser, 2007). Subterranean organisms depend on geological and hydrological structures and processes that govern the availability of suitable micro-habitats: air-filled voids or caves for troglofauna and aquifers that are not hypersaline for stygofauna (Environmental Protection Authority, 2016). Despite known links between subterranean fauna and geology and hydrology, it is difficult to predict the presence of subterranean fauna with confidence (e.g. Environmental Protection Authority, 2016) and sampling of subterranean organisms is difficult (see e.g. Thulin and Hahn, 2008). Direct measurements of the presence of subterranean fauna are relatively scarce in Sweden, as well as in many other parts of the world (Koch et al., 2024). Basic knowledge of these ecosystems is also often lacking (see e.g. review by Koch et al., 2024). Several different indicators relying on direct measurements (e.g. the number of different species of microorganisms and invertebrates or genes) are found in the reviewed literature (see Table 1). However, using these indicators that are based on firsthand data is likely unsuitable for a larger scale, as the sampling procedure would be exceedingly difficult (Thulin and Hahn, 2008).

Using national parks (or nature reserves) as an indicator is another approach suggested by e.g. Tognetto et al. (2021), to broadly map areas that could be important habitats. Nonetheless, such an approach would likely miss important subterranean habitats that have not been mapped as extensively as their surface counterparts. That said, translating the known links between subterranean fauna and geology and hydrology into generic geological units or formations to predict the presence of subterranean organisms is proposed as a possible way forward. Certain types of geology have been shown to have a higher likelihood of providing suitable subterranean fauna habitats than others. Alluvial formations in particular, fractured rock aquifers, weathered or fractured sandstone and karst landscapes have been found to support western Australia's subterranean fauna (EPA, 2016). Although Western Australia's subterranean fauna and climate might differ from the Swedish geological settings (see e.g., Guzik et al., 2011), the findings by Thulin and Hahn (2008) on groundwater fauna occurrences in Sweden support the assumption that similar geological and hydrological structures and processes could control the availability of suitable micro-habitats in the study area, with the addition that the hyporheic zone (and adjacent groundwater) is also a vital environment. At the scale of this study, geological formations outlined in the reports by EPA (2016) and Thulin and Hahn (2008) can be used to indicate the potential for habitat provision (see Table 4). Karst and alluvial formations, including the hyporheic zone, that are known to host the greatest diversity and number of microorganisms and invertebrates, are given the capacity class A. Porous rocks, such as sandstone and limestone, are given the capacity class B. For a detailed list of these geological formations, see Table S9 in the SM. The remaining geological formations and rocks are known to host both stygo- and troglofauna, but there is insufficient data to assign them to capacity classes. Our suggested indicator can highlight areas that are likely to have a more abundant presence of stygo- and troglofaunal (i.e., higher potential). However, additional indicators that can capture the potential for other subsurface species, such as fungi, should also be developed.

3.2.2.2. Indicators for groundwater-dependent ecosystems. The subsurface, in addition to providing micro-habitats for subterranean fauna, governs the availability of groundwater that some ecosystems depend on. This groundwater dependency can either be of continuous or seasonal character and consists of groundwater seepage or direct root uptake (Thorsbrink et al., 2016). Some groundwater-dependent ecosystems are more sensitive and vulnerable to groundwater level fluctuations than others. This sensitivity depends on the properties of the water supply of the ecosystem, which in turn is governed by geological and topographical conditions, hydrogeological properties of soil and rock, as well as the amount of runoff and groundwater formation (Thorsbrink et al., 2016; Werner and Collinder, 2011). There are several different sets of indices with sub-indicators that are suggested in the reviewed literature as indicators to map out the potential to provide a habitat for groundwater-dependent ecosystems (see e.g. Duran-Llacer et al., 2022; Fildes et al., 2023; Münch and Conrad, 2007; Pandey et al., 2023). Yet, these sets of indices refer to (semi-) arid areas that differ significantly from the study setting. Instead, the list of groundwater-dependent ecosystems suggested by Thorsbrink et al. (2016) is proposed in this study to map groundwater-dependent ecosystems in Sweden. Thorsbrink et al. (2016) based their work on Werner and Collinder (2011), who used the Swedish Environmental Protection Agency's species and nature guidelines for Natura 2000 (a European network of nature protection areas), along with hydrogeological type settings, to classify the sensitivity and vulnerability of different Swedish ecosystems. These ecosystems were additionally subdivided into three classes (low, medium and high) depending on their intrinsic sensitivity and vulnerability. For a detailed list of highly valued and groundwater-sensitive natural types in Sweden, see Table S10 in the SM. However, developing a broader and more data-intensive index as suggested in the reviewed literature would allow identification of ecosystems that are dependent on groundwater but are currently not included in the list by Thorsbrink et al. (2016).

3.2.3. Provisioning services

The section on provisioning services encompasses four distinct types of resources: (1) geomaterials, (2) groundwater, (3) geothermal energy and (4) underground space. Of the indicators highlighted in the literature review related to provisioning services (Table 1), four indicators are proposed without modification ('lithological units', 'gravel deposits', 'underground infrastructure density' and 'saline sandstone aquifers'), two were modified to fit the study setting ('groundwater extraction capacity' and 'geothermal gradient'), and four indicators with variations adapted to specific usages were suggested by the authors with variations adapted to specific usages (Table 4). Since there are no significant oil or gas resources present in Sweden, indicators for these resources have not been included. Similarly, there is no large-scale production of minerals for nutritional purposes. For suggestions on indicators related to these services, the reader is referred to Grima et al. (2023).

3.2.3.1. Indicators for provisioning of geomaterials. Provisioning of geomaterials refers to the potential to extract geomaterials from the subsurface. Geomaterials cover a wide range of materials, metals and minerals. Most of these geomaterials have well-established values and many resources are extensively mapped. Extraction of geomaterials has been divided into three specific services and six specific uses, which can be found in Table 4:

Table 4
Geophysical components contributing to provisioning geosystem services, related functions, indicators and assigned capacity class.

Geosystem service	Specific service	Specific use	Function	Suggested indicator	Suggested capacity classes for a Swedish setting		Reference(s)
Metallogenic minerals	Source of mineral substances	Metals used in a wide variety of applications (e.g. steel)	Concentration of metallogenic minerals	Metallogenic belt [-]	Lithological units with high potential	A	Eilu (2012), **see** Table S11 in the SM.
					Lithological units with good potential	B	
Industrial minerals	Source of mineral substances	Minerals used in a wide variety of applications (e.g. glass raw material)	Concentration of minerals with specific properties (e.g. low thermal conductivity)	Metallogenic belt [-]	Lithological units with high potential	A	Eilu (2012), **see** Table S11 in the SM.
					Lithological units with good potential	B	
Construction materials	Source of mineral substances	Inorganic materials used for road and railroad macadam	Concentration of inorganic materials with specific properties (e.g. high impact strength)	Lithological units [-]	Lithological units with high potential (≤40 M_{DE} + LA)	A	Arvidsson et al. (2023), **see** Table S11 in the SM.
					Lithological units with good potential (≤65 M_{DE} + LA)	B	
					Lithological units with some potential (≤90 M_{DE} + LA)	C	
		Inorganic materials used for concrete production	Concentration of inorganic materials with specific properties (e.g. good pumpability)	Soil deposits [-]	Gravel deposits (e.g. glaciofluvial deltas, eskers)	A	Grånäs et al. (2013)
				Lithological units [-]	Lithological units with high potential	A	Inferred from Møl Mortensen et al. (2023). **see** Table S11 in the SM.
					Lithological units with good potential	B	
					Lithological units with some potential	C	
		Inorganic materials used for filling purposes	Concentration of inorganic materials with specific properties (e.g. suitable grain sizes)	Lithological units [-]	Lithological units with good potential	A	Inferred from SGI (2017), **see** Table S12 in the SM.
					Lithological units with some potential	B	
					Lithological units with uncertain potential	C	
Ornamental resources	Source of mineral substances	Geomaterial used for decoration	Concentration of inorganic materials with desirable aesthetic properties	Lithological units [-]	Lithological units with high potential	A	**Authors' suggestion, see** Table S11 in the SM.
					Lithological units with good potential	B	
Groundwater for drinking	Source of water	Use of drinking water from the subsurface	The ability of the subsurface to store and transmit water	Groundwater extraction capacity [m^3/d]	High groundwater extraction capacity (>1500 m^3/d)	A	Inferred from Hjerne et al., 2021a, 2021b). **See** Table S13 in the SM.
Groundwater used as a material	Source of water	Use of water that can be used as a material (e.g. for cooling)			Medium groundwater extraction capacity (40–1500 m^3/d)	B	
					Low groundwater extraction capacity (<40 m^3/d)	C	
Geothermal resources	Source of energy	Using underground heat as an energy source	Underground temperature rises with increasing depth following the geothermal gradient	Geothermal gradient or Heat Flow [°C/km]	High geothermal gradient (>30 °C/km)	A	Inferred from Blackwell et al. (2006). **See** Table S14 in the SM.
					Medium geothermal gradient (20–30 °C/km)	B	
					Low geothermal gradient (<20 °C/km)	C	
Underground space	Source of space	Use of the deep subsurface to place vertical and horizontal constructions	Providing physical space (Underground cavity)	Underground infrastructure density [m^3/m^2]	Low underground infrastructure density (<0.01 m^3/m^2)	A	Bobylev (2016); Finesso and Van Ree (2022). **See** Table S15 in the SM.
					Medium underground infrastructure density (0.01–0.02 m^3/m^2)	B	
					High underground infrastructure density (>0.02 m^3/m^2)	C	
		Use of the near-surface subsurface to place vertical and horizontal constructions		Surface infrastructure density [-]	Low floor area ratio (<0.5)	A	**Authors' suggestion. See** Table S16 in the SM.
					Medium floor area ratio (1–0.5)	B	
					High floor area ratio (>1)	C	
Disposal and storage	Storage of CO_2 in porous media	Capture of CO_2 into long-term storage (CCS)	Providing physical space (Porous medium)	Saline sandstone aquifers [-]	Saline sandstone aquifers with high potential	A	Based on Møl Mortensen and Sopher (2021). **See** Table S17 in the SM.
					Saline sandstone aquifers with good potential	B	

(*continued on next page*)

Table 4 (*continued*)

Geosystem service	Specific service	Specific use	Function	Suggested indicator	Suggested capacity classes for a Swedish setting	Reference(s)
					Saline sandstone aquifers with some potential	C

Note: Sources are presented when available. If no suitable indicator was identified from the literature review, an indicator is suggested based on internal project team discussions. Class A – implies high potential, class B – implies some potential, class C – implies low potential, and class D – implies no or a limited potential. Suggested capacity classes are developed for a Swedish setting. SM = Supplementary Material.

(1) provisioning of (a) metallogenic and (b) industrial minerals;
(2) provisioning of construction materials for (i) railway macadam, (ii) concrete production, and (iii) filling material;
(3) provisioning of ornamental resources.

3.2.3.1.1. Indicators for metallogenic and industrial minerals. Sweden has a long tradition of mining and metal refining (i.e. provisioning of metallogenic and industrial minerals) and is one of the EU's leading ore and metal producers. Consequently, the potential of provisioning metallogenic[8] and industrial[9] minerals has been extensively mapped throughout the country with a substantial quantity of public exploration reports and maps (available through the SGU). Suggested indicators related to information on metal-, industrial mineral- and rock occurrences in the reviewed literature focus on the quantity of minerals extracted (Grima et al., 2023). However, this assessment only considers resources that are already in use and does not include the risk of sterilisation of resources. It is also not possible to assess the potential of deposits that are currently not in use, or the probable occurrences of metallogenic and industrial minerals.

Another approach is to correlate known deposits and active and closed mines with lithological units. This approach was used to create the Nordic Ore Deposit Database (NODD). See Eilu (2012) for a description of the database and its methodology. The database contains information on known metal-, industrial mineral- and rock deposits (both active and closed) as well as where there is potential for new discoveries (see Table S11 in the SM). This information is presented as 'metallogenetic areas' and 'industrial mineral deposit areas', which can be used to indicate the potential for provisioning of (a) metallogenic and, (b) industrial minerals. The database highlights two types of potentials that can be translated to capacity classes A and B: (A) 'areas of good exploration potential' that include most of the known occurrences and where it is assumed that the bedrock contains more deposits, and (B) areas with the 'highest potential for new discoveries' where the probability of further discoveries of economic deposits is especially high (Table 4).

3.2.3.1.2. Indicators for construction materials. Construction materials constitute the bulk of extracted geomaterials and have broad applications. This study focuses on geomaterial used in (i) asphalt and as railway macadam, (ii) component in concrete and (iii) a filling material. These different usages require different geomaterial properties, therefore, specific indicators are needed for each use (Table 4). In the reviewed literature, suggested indicators for construction materials focus on the quantity of materials extracted (Grima et al., 2023). However, as stated previously, this assessment only considers resources that are already in use. A practical approach to overcome this specific issue could be to develop a database that mimics the approach used to create the NODD database (i.e. correlate quarries or desirable rock properties to lithological units).

For asphalt and railway macadam (i), it is important that the parent rock can withstand abrasive wear and has high impact strength. Arvidsson et al. (2023) developed a classification system for rock material used in construction and building, based on resistance to wear (micro-Deval, MDE) and resistance to fragmentation (Los Angeles, LA). This system can be utilised in conjunction with lithological data to identify areas with high and good potential for extraction, although it does not account for factors such as accessibility or sustainability. For a few counties there are already rock quality maps showing the potential for extraction of high-quality rocks in the county (e.g. Schoning, 2021; Göransson and Lindgren, 2024). These rock quality maps typically also include accessibility and suitability assessments (e.g. highlighting conflicts of interests) as well as the projected demand of geomaterials in the county. However, nationwide rock quality maps are currently unavailable. Nevertheless, the information required for their creation, as well as methodological suggestions, is available (Arvidsson et al., 2023; Schoning, 2021; Göransson and Lindgren, 2024) and could potentially be used to create said map.

For concrete production (ii), aggregates have primarily been derived from two sources: (1) gravel extracted from glaciofluvial deposits and (2) crushed crystalline rock. Geomaterial from glaciofluvial deposits has traditionally been used in concrete production because the material is homogeneous, well-sorted and well-rounded. However, glaciofluvial deposits are finite resources which often constitute valuable groundwater resources and should be used sparsely. Crushed stone has increasingly been used as a replacement material for concrete production (Göransson, 2015). The crushed stone inherits its properties from the parent rock, and for concrete purposes, it is desirable for the material to have a low activity index and a low content of fine-grained quartz minerals, mica minerals and sulphides (Møl Mortensen et al., 2023). Using these parameters and correlating them to lithological units (or generic rock types) can be used to indicate areas that can have a good potential for extraction of materials for concreate production (see the reports by Møl Mortensen et al., 2023 for a nationwide map and Schoning and Mortensen, 2021, for a smaller scale map). For the use of geomaterials as a filling material (iii), a lower rock quality of the parent rock is often acceptable if the sulphide content (environmental concerns) and activity index (human health concerns) are sufficiently low and there is no contamination present. Annually, construction projects generate large quantities of construction rock which are often partially reused directly on site. Surplus masses (i.e. geomaterials that are not reused onsite), on the other hand, could be used to supplement or replace the extraction of new geomaterials in quarries (Nordström, 2017). For use as a filling material below buildings or hardened surfaces (e.g. areas that are asphalted, paved with stones, or covered in gravel), bedrock and sorted coarse-grained soils have the highest reusability potential, whereas peat and fine-grained soils have the lowest (SGI, 2017). For a detailed list of lithologies and their potential for reuse, see Table S12 in the SM. Anthropogenic materials can also be used as filling material. However, they were not included in this specific study as anthropogenic materials can be comprised of a very wide variety of materials with different technical properties. Filling material is also known to contain contaminants such as PAHs and metals. Hence, in our study, anthropogenic materials are treated as unknowns that require

[8] The following metals are included: Ag, Au, Be, Co, Cr, Cu, Fe, Li, Mn, Mo, Nb, Ni, Pb, Pd, Pt, Rh, REE, Sc, Sn, Ta, Ti, U, V, W, Y, Zn and Zr.

[9] The following industrial minerals are included: Andalusite, Anthophyllite, Apatite, Asbestos, Baddeleyite, Barite, Bentonite, Beryl, Calcite, Diamond, Dolomite, Feldspar, Fluorspar, Garnet, Graphite, Ilmenite, Kaolin, Kyanite, Muscovite, Nepheline, Olivin, Petalite, Phlogopite, Quartz, Shungite, Sillimanite, Spodumene, Talc, Vermiculite, Wollastonite.

detailed sampling.

3.2.3.1.3. Indicators for ornamental resources. A wide range of geomaterials is used for ornamental purposes (e.g. jewellery and façades). The suggested indicators in the reviewed literature on ornamental resources focus on the quantity of mineral resources extracted (Grima et al., 2023) or using a geodiversity index as an indicator of potential (Ahmadi et al., 2021; de Paula Silva et al., 2021; Pereira et al., 2013; Silva et al., 2013). However, focusing only on resources that are already in use limits practical applicability. To overcome this issue, a database that mimics the approach used to create the NODD database could be used (i.e. correlating quarries or desirable rock properties to lithological units). The NODD database contains information on gemstones (e.g. beryl), and precious and semi-precious metals (e.g. silver and gold). For geomaterials used as stone veneer, sculptures or dimension stones[10], the database needs to be complemented. This could be done by correlating quarries (especially those that relate to Geoheritage Stones or façades on buildings with a cultural value) to lithological units. Information on lithological units is available through the SGU, but data on Geoheritage Stones is spread across different databases.

3.2.3.2. Indicators for provisioning of groundwater for drinking and use as a material[11]. Access to drinking water is critical for society. In Sweden, groundwater (natural and artificially recharged) accounts for approximately 40% of the total municipal water supply (SCB, 2022). Groundwater resources used as drinking water supply must be included in comprehensive plans, but to limit activities that can degenerate future groundwater resources and avoid sterilisation of resources, it would be desirable to also map potential future resources. There are several indicators proposed in the reviewed literature referring to this service, such as 'current groundwater extraction' (Grima et al., 2023), 'groundwater head' (Czúcz et al., 2018) and 'potential extraction capacity' (Hjerne et al., 2021a, 2021b). Of these indicators, 'potential extraction capacity' is proposed as it also includes resources not yet exploited and is less sensitive to seasonal variations. The SGU has made estimates of the quantity of groundwater that can be extracted (groundwater map), which, together with expert judgement, is also the basis to assign suggested capacity classes (Table 4). Groundwater reservoirs in this map are divided into two types; (1) large, mainly glaciofluvial deposits and parts of the sedimentary bedrock, and (2) small, mainly till, fine-grained soils or crystalline bedrock (Hjerne et al., 2021b). Small reservoirs have a relatively small capacity due to their limited volumetric extent and/or effective porosity and are meant for individual water supply.[12] The assigned capacity classes aim to capture different generalised aquifer types where class A (>1500 m^3/day) is typically found in glaciofluvial sediments (such as eskers or deltas), class C (<40 m^3/day) is typically found in till or the crystalline bedrock, and class B (40–1500 m^3/day) is given to the aquifers that are in-between these values (see Table S13 for details). The separation of larger and smaller reservoirs in the available data could warrant further subdivision into the specific services of drinking water for (a) municipal use and (b) individual use.

3.2.3.3. Indicators for provisioning of geothermal energy. Geothermal energy refers to the use of energy derived from the inner heat of the earth. In Sweden, this heat is only accessible via deep boreholes (approximately 500- 5000 m) and through the extraction of groundwater or by heat exchange in geological formations. Until recently, the exploitation of this service in Sweden was limited due to comparably low temperatures in the bedrock and the need for deep boreholes, which are associated with high drilling costs. However, advancements in drilling technology are rapidly reducing these costs (Song et al., 2023), making deep geothermal systems more feasible in Sweden.

A promising indicator for the potential of geothermal energy is the temperature gradient (Blackwell et al., 2006), which shows the increase in temperature with depth. This gradient is not spatially uniform: it depends on geological structures and processes and some places have a higher geothermal gradient than others (see review by Jolie et al., 2021). The geothermal gradient in Sweden is generally low (see e.g. Erlström et al., 2016), but in areas with thick layers of sedimentary rocks that have low thermal conductivity or radioactive crystalline rocks, the geothermal gradient can be higher (Blackwell et al., 2006). Nationwide geothermal gradient maps showing this heterogeneous distribution are not currently available for Sweden. There are, however, site-specific investigations (see e.g. Rosberg and Erlström, 2021; Sundberg et al., 2009) and global heat flow estimates available (Lucazeau, 2019). That said, the global heat flow estimates are too generalised for the specific study scale. The capacity classes for provisioning of geothermal energy (see Table 4) are based on estimates for the United States by Blackwell et al. (2006) and may require rebalancing as more detailed geothermal data for Sweden is released. Class A is suggested at >30 °C/km, class B at 20–30 °C/km and class C at <20 °C/km (see Table S14 in the SM). Considering the low thermal gradient of the Fennoscandia shield area, practically all of Sweden is expected to be in the lower classes.

3.2.3.4. Indicators for provisioning of underground space for construction. The subsurface is increasingly used to relieve a congested surface by placing various structures below ground. However, once an underground construction is completed, it becomes a permanent feature, stressing the need for long-term planning of subsurface space utilisation, as well as reinforcing the view that underground space can be viewed as a resource that can be 'extracted'. Indicators for underground space use are typically difficult as the spatial distribution and depth of underground infrastructure are often confidential (Nordström, 2017). The standard indicators found in the literature thus estimate the presence of underground infrastructure using available records (e.g., road maps marked with tunnels, subway maps, geo-energy wells, etc) and multiplying these features by a standard volume to get an estimate of the volume used. However, this does not consider that different structures are located at different depths (see e.g. Nordström, 2017). Therefore, this service is divided into two separate services: use of near-surface underground space, and use of deep underground space (see e.g. Griffioen et al., 2014). For near-surface underground space, a surface building density map can be utilised to highlight areas with high versus low potential. It can be assumed that districts with a high building density will have a high density of pipes, cables, and other horizontal structures placed in the near-surface subsurface. Therefore, it is proposed that the floor area ratio (FAR) be used as an indicator for shallow underground space. An area with a high FAR is assumed to have low potential, and vice versa. Based on the FAR reported for the different city districts of Malmö (the third largest Swedish city) in Donnerhack et al. (2018), a FAR less than 0.5 is suggested to be assigned a class A, a FAR between 1 and 0.5 to class B, and a FAR greater than 1 to class C (see Table S15 in the Supplementary Material). The deep subsurface, on the other hand, can be described by an underground infrastructure density index as suggested by Bobylev (2016) and Finesso and Van Ree (2022). For both indices, lower density translates to higher potential (i.e., more space is available). Based on the underground infrastructure densities reported for Swedish cities in Bobylev (2016), a density less than 0.01 m^3/m^2 is suggested to be assigned a class A, a density between 0.01 and 0.02 m^3/m^2 to class B, and a density greater than 0.02 m^3/m^2 to class C (see Table S16 in the SM). While information on surface constructions is typically readily available, information on underground constructions (e.g. tunnels and rock caverns) is often restricted by the Swedish

[10] A dimension stone is regarded as an ornamental resource in this study, notwithstanding that dimension stones have extensively been used as load-bearing construction elements.

[11] The division of groundwater used as drinking water or as a material stem from the CICES classification. See Lundin-Frisk et al. (2022) for more details

[12] Defined in the European Drinking Water Directive as less than 10 m^3/d or serves less than 50 people.

Protection Act (2010:305), which limits the availability of both technical and spatial aspects of these constructions (Kuchler et al., 2024). Hence, information related to this specific indicator can be difficult to access.

3.2.3.5. Indicators for provisioning of underground space for disposal and storage. A porous geological stratum can be used to store and dispose of a variety of different substances, but no indicators relating to this were found in the literature review. The focus of this study is on the use of the subsurface for Carbon Capture and Storage (CCS), which is currently being investigated in Sweden (Møl Mortensen and Sopher, 2021). There are several methods for underground storage of CO_2: injecting CO_2 into deep saline aquifers, depleted oil and gas fields, or by mineral trapping using porous basic rocks, such as basalts, to mineralise CO_2 through chemical reactions (Møl Mortensen and Sopher, 2021; Teir et al., 2010). In Sweden, the potential to store CO_2 in hydrocarbon fields or by mineral trapping is negligible (Anthonsen et al., 2013), as the dominating Precambrian crystalline basement lacks sufficient porosity and permeability for CO_2 storage (O'Neill et al., 2014; Teir et al., 2010). However, some storage potential may exist in the thicker Cambrian sequences in the south-west of Skåne and the Baltic Sea (Anthonsen et al., 2013; O'Neill et al., 2014; Teir et al., 2010). To indicate areas that are of interest for CCS use at a national scale, geological formations known to host deep (>800m) saline aquifers (see Table S17 could be used as an indicator (Møl Mortensen and Sopher, 2021). To assess whether an identified storage site is suitable, a thorough investigation is required (see Directive, 2009/31/EC of the European Parliament and the Council for requirements).

3.2.4. Cultural services

The section on cultural services encompasses four specific services: (1) sacred and historical sites, (2) iconic sites (e.g. related to geotourism), (3) scientific resources and (4) geoeducational resources. Of the indicators related to cultural services in the reviewed literature (Table 1), two indicators ('geosite' and 'geotope') are proposed without modification (Table 5).

3.2.4.1. Indicators for sacred and historical sites, iconic sites, geoscientific sites and geoeducational sites. The geological stratum, in addition to forming the substructure for the environment (and its associated visual appeal), shapes natural environments that are used to enhance human well-being by, for example, providing opportunities for geotourism or recreation (Lundqvist and Dahl, 2020; Schoning et al., 2019). The local geology can also be part of the area's identity and is reflected in, among other things, how we perceive our surroundings and the names of places, such as 'the High Coast', which is part of a UNESCO World Heritage Site (see e.g. Schoning et al., 2019), and 'Bergslagen', renowned for its (historical) mining and metallurgical industry. Hence, mapping geological features and underlying processes is part of understanding how natural and cultural values may be co-constructed through the interaction of humans and the natural environment and how they can be preserved, managed and used. Although geotourism or recreation and aesthetically pleasing environments are often associated with the surface, there are several instances where these relate to the subsurface. For example, the nearly 4.5 km long karst cave 'Lummelundagrottan' on Gotland is an important tourist attraction that also aesthetically influences the surrounding nature with numerous sinkholes and springs along its course.

The literature review highlights several different indicators for cultural services related to different specific uses (e.g. number of employees [n] and enterprises [n] related to tourism). However, most indicators suggested in the literature are targeted towards assessing the demand (social and economic system) rather than the potential of providing these services (geophysical environment), as can be seen in Tables 1 and 2 In other words, most of the indicators related to cultural services in the reviewed literature can be described as composite indicators. Only two indicators ('geotope' and 'geosite') refer specifically to the geophysical environment. While indicators such as Aesthetic Value Index (Grima et al., 2023, referring to Sherrouse et al., 2011) and number of symbolic species (Grima et al., 2023) are useful, they tend to focus on the biophysical environment rather than the geophysical environment. Instead, Fassoulas et al. (2012) suggested geotopes as a possible indicator that focuses more on the geophysical environment. Similarly, in the report on Geological Heritage in Inner Scandinavia, the GEARS project (Lundqvist and Dahl, 2020), suggested geotopes and geosites as quantifiable indicators.

Lundqvist and Dahl (2020) define a geotope as a delimited area with a specific geological setting (e.g. ravine, cave or esker), whereas a geosite is a designated area with cultural or historical values (e.g. mythological or aesthetic links to human activity, the first observation of

Table 5
Geophysical components contributing to cultural geosystem services, related functions, indicators and assigned capacity class. Suggested capacity classes are developed for a Swedish setting. SM = Supplementary Material.

Geosystem service	Specific service	Specific use	Function	Suggested indicator	Suggested capacity classes for a Swedish setting		Reference(s)
Sacred and historical sites	Elements of nature that have symbolic, sacred or religious meaning	Spiritual, symbolic and other interactions with the natural environment	Providing elements of the environment that are important as symbol	Geosite Geotopes	List of geosites List of geotopes	A	Fassoulas et al. (2012); Lundqvist and Dahl (2020). **See** Tables S18 and S19 in the SM.
Iconic sites	Recreation (inclusive tourism) Contributing to aesthetic environments	Using the environment for sport and recreation Appreciation of the environment (e.g. cultural landscape linked to previous mining activities)	Providing suitable environments that are engaged with, used or enjoyed	Geosite Geotopes	List of geosites List of geotopes	A	Fassoulas et al. (2012); Lundqvist and Dahl (2020). **See** Tables S18 and S19 in the SM.
Geoscientific sites	Scientific resource	Intellectual interactions with the natural environment	Providing elements that are important for research on the evolutionary history of the earth and current geological processes	Geosite Geotopes	List of geosites List of geotopes	A	Fassoulas et al. (2012); Lundqvist and Dahl (2020). **See** Tables S18 and S19 in the SM.
Geoeducational sites	Educational resource	Intellectual interactions with the natural environment	Providing elements that are important for studying the evolutionary history of the earth and current geological processes	Geosite Geotopes	List of geosites List of geotopes	A	Fassoulas et al. (2012); Lundqvist and Dahl (2020). See Tables S18 and S19 in the SM.

Note: Sources are presented when available. If no suitable indicator was identified from the literature review, an indicator is suggested based on internal project team discussions. Class A – implies high potential, class B – implies some potential, class C – implies low potential, and class D – implies no or a limited potential.

a particular feature reported). Please note, however, that this broader definition of geotope and geosite is not universally agreed upon. A more common definition of a geosite restricts it to sites with scientific value, whereas sites with aesthetic, touristic, educational, or other values are referred to as geodiversity sites (see Brilha, 2016). Using the definition proposed by Lundqvist and Dahl (2020), geotope and geosits would cover all four services because the same indicator(s) can be used for all services separately, whereas using the stricter definition (see Brilha, 2016) would require additional indicators to be developed. For simplicity, we therefore recommend using geotopes and geosites as defined by Lundqvist and Dahl (2020) as indicators for all the listed cultural services (see Tables S18–19 in the SM), although they are not ideal due to double counting issues arising from the difficulty in disentangling the services from each other. That said, for the purpose of merely highlighting areas that could potentially supply these services, double counting is not necessarily problematic. Nonetheless, to capture the potential of the physical environment to provide services to society, the geophysical environment should also be complemented by the biophysical environment (i.e. combining ecosystem services and geosystem services).

3.3. Wider considerations - limitations and scientific gaps

The suggested set of indicators can be used to visualise the potential of the geophysical environment to deliver specific geosystem services and make the subsurface more visible in spatial planning and natural resource management. The literature review of peer-reviewed publications and technical reports in this study identified 75 indicators that could be used to map different geosystem services. Although there are several suggested sets of indicators for ecosystem services (e.g. Czúcz et al., 2021; Grima et al., 2023), few have included any indicators that relate to geophysical structures and processes of the subsurface. For example, the service of water retention is typically viewed as 'biotic' or 'biophysical' with 'wetland' and 'vegetation cover' as common indicators (e.g. Grima et al., 2023). The indicators suggested in our study can be used to highlight that the subsurface and the geophysical environment can also provide essential services, of which some have not received as much attention as their biophysical counterparts. That said, it should be noted that our suggested set of indicators is developed for a Swedish geological setting given the type of data and information available for Sweden, hence, specific indicators may be less suited to a different geological setting.

While most of the reviewed studies did not specifically mention geosystem services, there were descriptions of geophysical structures and processes relevant to this study. Although an extensive set of indicators is suggested in this study, it should not be considered exhaustive. The suggested indicators relate to a specific use of a given geosystem service. For example, the ability of the unsaturated zone to improve the quality of infiltrating stormwater is just a subset of the geosystem service regulation of water quality. Groundwater quality is also altered and typically improved in the saturated zone, but to capture this process would require other indicators. It is therefore imperative to be precise regarding which geosystem service an indicator is targeting. It should also be noted that, from a planning perspective or in decision support tools, it is crucial to include both potential services (i.e., those providing benefits when utilised) as well as risks or disservices. However, this specific study focuses on services rather than disservices, as services from the subsurface are often less acknowledged than their disservice counterparts but are equally important to consider in the planning process (see e.g., van der Meulen et al., 2016).

The suggested indicators were developed at a national scale, where the geological variation is generally much greater compared to a regional or municipal scale. Therefore, the division into capacity classes may need to be adjusted for some indicators to meet the need at a smaller scale: for example, in a region or municipality with only sedimentary rocks, there is likely a need to differentiate between different types of sedimentary rocks to assess the potential for underground construction, instead of having all sedimentary rocks be classified with the same potential. Accordingly, the proposed indicators, while potentially useful in highlighting potentials or lack thereof, are insufficient for localisation studies on their own and are unsuitable for the design of various underground structures, which require site-specific investigations. Nevertheless, environmental indicators, such as those proposed in this study, are a well-established method for facilitating communication (e.g. Czúcz and Arany, 2016; Müller et al., 2016) and can consequently enhance awareness of the subsurface and its integration into spatial planning.

The rationale for using capacity classes rather than a semi-quantitative scoring system to indicate a potential is done to emphasise that the indicators should be applied with due consideration in a specific area and with a comprehensive sustainability perspective. As stated, the indicators and assigned potentials are sensitive to the area to which they are applied: low potential in one specific region can be regarded as high elsewhere. Further, the classes refer to the maximum potential that the indicator can provide, but this can fluctuate over time. For example, the ability of the subsurface to regulate groundwater quantity by retaining stormwater can be less effective during winter when the ground is frozen, which limits the quantity of water that can infiltrate into the strata.

The indicators presented in this study represent the first three parts of the cascade model where (1) different geophysical structures and processes have a certain potential to (2) provide functions and (3) deliver services. Society can harness these potentials through different actions that trigger flows of services from 'nature' to society. For example, only when minerals are mined and further processed is the flow of geomaterials activated to fulfil human needs in the form of goods. Hence, it is important to distinguish between the potential of geosystem services and the actual benefit to society. For assessing and visualising the full cascade, the suggested set of indicators needs to be complemented by the benefits and values associated with these geosystem services. The benefits derived from geosystem services in an area do not only depend on the potential of the environment to deliver geosystem services but also on how society values these services, i.e. the present and future demand for them, and how accessible they are. Even if a potential for services exists at a given site, it must be accessible to be activated into a flow, and subsequently, a benefit. If, for example, the potential exists in a protected area (or beneath a city), its utilisation may not be allowed by law, or it might be too expensive to access. The suggested indicators can thus identify areas of high potential for geosystem services, but this potential may not necessarily translate into actual use due to low accessibility.

Several of the proposed indicators in this study overlap at least to some extent. For example, permeable soil can provide several functions (e.g. retention of stormwater, filtration of water, maintaining groundwater levels) that can be used to derive different geosystem services (e.g. regulation of flooding events, removal of harmful substances, maintaining porewater pressures, maintaining groundwater dependent ecosystems). If the purpose of using the suggested indicators is to visualise areas that have the potential to deliver geosystem services, this might not be of great concern. However, if the geosystem services are to be valued, this could raise an issue of double counting unless only final services are valued (see e.g. Lundin-Frisk et al., 2024, for geosystem services and Fu et al., 2011 for ecosystem services), and a sensitivity analysis might be warranted. Referring to these double counting issues, recent contributions to environmental economics have emphasised the necessity of focusing on final services rather than intermediate services, where the latter typically include supporting services (Lundin-Frisk et al., 2024). However, as noted by e.g. De Groot (2006), van der Meulen et al. (2016) and van Ree and van Beukering (2016) some of the services that are viewed as supporting geosystem services relates to carrier functions of the geological substrate and thus can be directly utilised to derive a benefit (i.e., a final service). Therefore, it would be desirable, both from a spatial mapping perspective as well as from a valuation point of view, to have a unified definition of geosystem service that mimics the CICES approach to ecosystem services, where the definition of each service consists of both an "ecological clause", describing the biophysical output, and a "use clause", describing the contribution it makes to an eventual benefit.

Although the concept of geosystem services is not yet fully developed or agreed upon by academics and decision-makers (see review by Lundin-Frisk et al., 2022), and to some extent overlaps with the more established ecosystem services concept, geosystem services can play an instrumental role in improving the management of subsurface resources. The present study makes a novel contribution to that end, as the suggested set of indicators for Sweden provides a starting point for the continuation of developing indicators that can cover the multitude of services that stem from the subsurface, including those in the review of Lundin-Frisk et al. (2022), as well as the geophysical services listed in the new revision of CICES (Haines-Young, 2023).

4. Concluding remarks

The main conclusions and contributions of this study are summarised below.

- The literature review of indicators that could be utilised for the mapping of geosystem services reveals a diverse set of indicators, ranging from direct measurements to indices composed of sub-indicators. This diverse set of indicators includes both those that focus on the potential supply of a given service and broad composite indicators. The review resulted in a gross list of 75 indicators that were interpreted by the authors as useful for geosystem services mapping. However, the review also highlighted that a comprehensive set of indicators that capture the full range of services that the subsurface can potentially offer is currently lacking.
- A curated list of 21 indicators for geosystem services was developed for a Swedish setting, based on the gross list derived from the literature review. 11 indicators were used without modification, 5 were modified to fit the specific study setting and 5 new indicators were developed. All indicators focus on the potential supply of services derived from the geophysical environment and are assigned a capacity class that describes their capacity to deliver a specific service at a nationwide scale. The curated list includes indicators for regulating, supporting, provisioning and cultural services. All but two of the suggested indicators can be directly applied using Swedish and Nordic open-access databases and maps to visualise the potential supply of specific geosystem services in the study setting.
- The curated list of indicators encompasses a wide range of services from the subsurface. However, the actual use of specific geosystem services should always be assessed within a specific context and a comprehensive sustainability perspective, including evaluations of accessibility and the importance or value of these services to society. Nevertheless, the curated list of indicators serves as a starting point for further development and refinement of indicator sets that can be used to highlight the 'invisible' subsurface and the services it provides to society.

CRediT authorship contribution statement

Emrik Lundin-Frisk: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lars O. Ericsson:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Paula Lindgren:** Writing – review & editing, Investigation, Funding acquisition. **Lorena Melgaço:** Writing – review & editing, Funding acquisition. **Fredrik Mossmark:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Olof Taromi Sandström:** Writing – review & editing, Investigation, Funding acquisition. **Victoria Svahn:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization. **Tore Söderqvist:** Writing – review & editing, Investigation, Funding acquisition. **Yevheniya Volchko:** Writing – review & editing, Supervision, Funding acquisition. **Maria de Lourdes Melo Zurita:** Writing – review & editing, Funding acquisition. **Jenny Norrman:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100609.

Appendix

List of articles identified in the literature study

The following articles and reports were identified in the literature study.

Scientific literature

1 Ahmadi, M., Mokhtari, D., Khodadadi, M., & Shahabi, H. (2021). Geodiversity evaluation and geoconservation using grid analysis: case study, north of Ilam Province. Applied Geomatics, 13(4), 537–553. https://doi.org/10.1007/s12518-021-00377-0

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List of unique indicators derived from the reviewed literature

The indicators identified in the literature review are to some extent overlapping. In the following table the indicators have been merged to create a list of 'unique' indicators for geosystem services.

Table A1
List of 'unique' indicators for geosystem services.

Indicator [unit]	For	Source
Quantity of mass flows regulated	Regulation of mass movements	Haines-Young and Potschin-Young (2018)
Quantity of minerals produced	Industrial minerals	Grima et al. (2023); Haines-Young and Potschin-Young (2018)
	Metallogenic resources	Grima et al. (2023); Haines-Young and Potschin-Young (2018)
Quantity of raw materials produced	Construction materials	Grima et al. (2023); Haines-Young and Potschin-Young (2018)
Quantity of salt produced	Minerals for nutritional purposes	Grima et al. (2023); Haines-Young and Potschin-Young (2018)
Quantity of water filtered	Regulation of water quantity	Grima et al. (2023); Haines-Young and Potschin-Young (2018)
	Regulation of water quality	Grima et al. (2023) referring to Laterra et al. (2012)
Biochemical degradation capacity	Regulation of water quality	Grima et al. (2023) referring to Böhnke-Henrichs et al. (2013)
Current groundwater extraction	Groundwater for drinking	Grima et al. (2023)
	Groundwater as a material	Grima et al. (2023)
Developed surface space	Underground space	Peng and Peng (2018)
Developed underground space	Underground space	Bobylev (2016); Finesso and Van Ree (2022); Peng and Peng (2018)
Developed underground space per person	Underground space	Bobylev (2016); Finesso and Van Ree (2022)
Dissolved oxygen	Habitat provision	EPA (2016); Thulin and Hahn (2008)
Electric conductivity	Habitat provision	EPA (2016); Thulin and Hahn (2008)
Employment	Iconic sites	Czúcz et al. (2018)
Fossil fuel extracted	Non-renewable energy resources	Grima et al. (2023); Haines-Young and Potschin-Young (2018)
Gamma-ray radiation	Regulation of soil and bedrock chemistry	Jelinek and Eliasson (2015)
Geothermal gradient or heat-flow	Geothermal resources	Duffield and Sass (2003)
Groundwater level	Groundwater for drinking	Czúcz et al. (2018)
	Groundwater as a material	Czúcz et al. (2018)
Hydraulic conductivity in rocks	Groundwater for drinking	Hjerne et al. (2021a)
	Groundwater as a material	Hjerne et al. (2021a)
Hydrogeological units	Habitat provision	EPA (2016)

(continued on next page)

Table A1 (*continued*)

Indicator [unit]	For	Source
Indexes composed by sub-indicators	Iconic sites	Grima et al. (2023) referring to (Sherrouse et al., 2011)
	Regulation of water quantity	Grima et al. (2023); Vandecasteele et al. (2018)
	Groundwater dependent ecosystems	Cruz et al. (2022); Duran-Llacer et al. (2022); El-Hokayem et al. (2023); Fildes et al. (2023); Gou et al. (2015); Link et al. (2023); Münch and Conrad (2007); Pandey et al. (2023)
	Regulation of erosion	Czúcz et al. (2018)
	Regulation of mass movements	Czúcz et al. (2018)
	Non-renewable energy resources	Ahmadi et al. (2021); de Paula Silva et al. (2021); Pereira et al. (2013); Silva et al. (2013)
	Industrial minerals	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)
	Metallogenic resources	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)
	Ornamental resources	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)
Legal protection	Habitat provision	Tognetto et al. (2021)
Lineament density	Regulation of stress and strain	Peng and Peng (2018)
Metallogenic belt	Construction materials	Eilu (2012)
	Industrial minerals	Eilu (2012)
	Metallogenic resources	Eilu (2012)
Number of deep saline aquifers	Disposal and storage (CCS)	Møl Mortensen and Sopher (2021); Teir et al. (2010)
Number of enterprises	Iconic sites	Czúcz et al. (2018)
Number of genes	Habitat provision	Steube et al. (2009)
Number of geologically interesting sites	Iconic sites	Schoning and Lundqvist (2020)
	Scientific and educational resources	Schoning and Lundqvist (2020)
Number of geoparks	Iconic sites	Tognetto et al. (2021); Schoning and Lundqvist (2020)
	Scientific and educational resources	Tognetto et al. (2021)
Number of geotopes	Iconic sites	Fassoulas et al. (2012); Lundqvist and Dahl (2020)
	Scientific and educational resources	Fassoulas et al. (2012); Schoning and Lundqvist (2020)
Number of microorganisms & invertebrates	Habitat provision	Steube et al. (2009)
Number of people participating in sacred activities	Sacred and historical sites	Grima et al. (2023); Haines-Young and Potschin-Young (2018)
Number of springs	Groundwater for drinking	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)
	Groundwater as a material	Ahmadi et al. (2021); Pereira et al. (2013); Silva et al. (2013)
Symbolic species	Groundwater dependent ecosystems	Thorsbrink et al. (2016); Söderqvist et al. (2014)
	Iconic sites	Grima et al. (2023)
Number of wells	Groundwater for drinking	Czúcz et al. (2018)
Permeability index	Regulation of water quantity	Carlsson et al. (2020); Lewis et al. (2006)
pH	Habitat provision	EPA (2016); Thulin and Hahn (2008)
Potential extraction capacity	Groundwater for drinking	Grima et al. (2023); Haines-Young and Potschin-Young (2018); Hjerne et al. (2021b)
	Groundwater as a material	Grima et al. (2023); Haines-Young and Potschin-Young (2018); Hjerne et al. (2021b)
Potential geothermal power capacity	Geothermal resources	Grima et al. (2023) referring to Cook et al. (2017)
Reduced flood risk area	Regulation of water quantity	Czúcz et al. (2018)
Slope stability ratio	Regulation of mass movements	Grima et al. (2023) referring to (Band et al., 2012)
Soft ground thickness	Regulation of stress and strain	Peng and Peng (2018)
Soil eroded	Regulation of erosion	Czúcz et al. (2018)
	Regulation of mass movements	Czúcz et al. (2018)
Soil erodibility	Regulation of erosion	Mallinis et al. (2023)
	Regulation of erosion	SGI (2023)
Soil instability	Regulation of mass movements	SGI (2023)
Soil uniformity	Regulation of stress and strain	Peng and Peng (2018)
Storage and permeability capacity	Regulation of water quantity	Czúcz et al. (2018)
Sulphur content	Regulation of soil and bedrock chemistry	Trafikverket (2015)
Terrain classes	Regulation of stress and strain	SGI (2016)
Thermal conductivity	Regulation of temperature by the subsurface	Erlström et al. (2016)
Time spent	Scientific and educational resources	Grima et al. (2023)
Underground premises floor area	Underground space	Bobylev (2016)
Urban underground infrastructure density (UUID)	Underground space	Bobylev (2016); Finesso and Van Ree (2022)
Visitor numbers	Iconic sites	Fox et al. (2022); Grima et al. (2023); Haines-Young and Potschin-Young (2018); Stanley et al. (2023)
	Sacred and historical sites	Czúcz et al. (2018); Haines-Young and Potschin-Young (2018)

Data availability

Data will be made available on request.

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