Improved assessments of subsurface projects: Systematic mapping of geosystem services and a review of their economic values

Citation for the original published paper (version of record):
Lundin Frisk, E., Soderqvist, T., Merisalu, J. et al (2024). Improved assessments of subsurface projects: Systematic mapping of geosystem services and a
review of their economic values. Journal of Environmental Management, 365.
http://dx.doi.org/10.1016/j.jenvman.2024.121562

(article starts on next page)

Journal of Environmental Management 365 (2024) 121562

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Improved assessments of subsurface projects: Systematic mapping of geosystem services and a review of their economic values

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ARTICLE INFO

Handling editor: Jason Michael Evans

Keywords:
Cost-benefit analysis
Subsurface planning
Geomaterial extraction
Tunnel construction
Underground space
Ecosystem services

ABSTRACT

Awareness of the subsurface and its multitude of resources is generally low and decisions on access to subsurface resources are often guided by a ‘first come, first served principle’. Although not yet fully developed, the concept of geosystem services has been put forward to make subsurface resources more visible and acknowledged in decision-making. This study (1) illustrates a systematic mapping of effects on geosystem services using a process-oriented perspective in two conceptual case studies; (2) translates the mapped effects into costs and benefits items in a qualitative cost-benefit analysis (CBA) context; and (3) presents a systematic review of economic valuation studies of geosystem services to investigate the available support for a quantitative CBA. The findings suggest that systematic mapping of effects on multiple geosystem services can inform different types of assessment methods and decision-makers on trade-offs and provide a basis for well-informed and responsible decisions on subsurface use. Combining such mapping with a CBA can further strengthen decision support through indications of the net effects on human well-being. However, although economic valuation of non-market geosystem services is possible using established valuation methods, such studies are scarce in scientific literature. Thus, although a CBA can provide a basis for supporting decisions on subsurface use from a consequentialist perspective, full quantification of all effects may require great efforts, and it needs to be complemented with other methods to capture the full range of values the subsurface can provide. This study also highlights that depending on the context, supporting and regulating geosystem services can be either intermediate or final services. Therefore, if geosystem services are to be included in the abiotic extension of CICES, in which supporting services by definition are excluded, reclassification of the supporting geosystem services should be considered not to risk being overlooked in economic valuation and CBA.

Funding

Our funders are gratefully acknowledged for financial support: the Geological Survey of Sweden (Dnr 36–1911/2019), the Rock Engineering Research Foundation (BeFo 429) and the Richertska Foundation (2019-00563).

1. Introduction

1.1. Background

Decisions on access to the subsurface are often guided by a first come, first served principle (Admiraal and Cornaro, 2016; Dick et al., 2017; SGU, 2015; Stones and Heng, 2016; Tengborg and Sturk, 2016). Such decisions may lead to intra- and intergenerational conflicts of interest as utilisation of one subsurface resource at one point in time may inhibit, or severely limit, utilisation of other subsurface resources in the future and may impede sustainable development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). A structured way of exploring the linkages between the effects of a planned subsurface use and the different services that the subsurface provides would be desirable to support decisions which consider consequences for both present and future generations.

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https://doi.org/10.1016/j.jenvman.2024.121562
Received 16 October 2023; Received in revised form 1 June 2024; Accepted 18 June 2024
Available online 29 June 2024

Geosystem services in broad terms refer to the contributions to human well-being from goods and services[1] derived from subsurface (van Ree and van Beukering, 2016) or abiotic (Gray, 2011) structures and processes, and thus have an instrumental value in the social and economic system. By contrast, ecosystem services refer to "the contributions that ecosystems (i.e., living systems) make to human well-being" (Haines-Young and Potschin-Young, 2018, p. 3). However, while this separation between the biotic and abiotic parts of nature in many cases is arbitrary (e.g. Fox et al., 2020), the idea of 'geosystem services' has arisen due to a lack of acknowledgement of the role of subsurface and abiotic components of nature in studies related to ecosystem services and other environmental frameworks (see e.g. Gray, 2011, 2018; van Ree et al., 2017). Although not yet fully developed (see review by Lundin Frisk et al., 2022), geosystem services have been put forward as a concept that can make subsurface resources more visible and acknowledged (Bobylev et al., 2022; Kuchler et al., 2024; Lundin Frisk et al., 2022; van Ree et al., 2017, 2024; Volchko et al., 2020). As such, it has the potential to serve as a point of departure for a systematic mapping of (positive and negative) effects of subsurface projects, focusing on geosystem services derived from the subsurface (Lundin Frisk et al., 2022; van Ree and van Beukering, 2016; van Ree et al., 2017; Volchko et al., 2020).

Several assessment and decision-support methods can be used to evaluate the impacts of a proposed project and investigate how a project can be improved to mitigate various negative effects or to evaluate whether a proposed project is beneficial. Environmental impact assessment (EIA), multi-criteria decision analysis (MCDA), life-cycle analysis (LCA) and various financial and economic methods including cost-benefit analysis (CBA) are examples of such methods, but common for all is that effects that are not mapped or considered will not be included in any method or tool. Using geosystem services as a starting point, effects due to impacts from proposed future subsurface projects can be systematically mapped and included in different types of assessments and decision support tools to evaluate whether the positive effects outweigh the negative ones, facilitating a sustainable use and management of the subsurface.

Cost-benefit analysis (CBA) is widely applied with respect to both countries and policy areas (Boardman et al., 2018), facilitated by well-developed theoretical foundations (e.g. Johansson and Kriström, 2016, 2018) and practical guidelines produced by international and national agencies. See e.g. Abelson (2020) for a review of such guidelines and OMB (2023, 2024) for recent examples. CBA takes into consideration positive and negative effects on human well-being (i.e., benefits and costs, respectively) on a societal level, including present and future generations, and relies on welfare economics for expressing benefits and costs in monetary units (Johansson and Kriström, 2016, 2018). The societal perspective of CBA implies that externalities must be included in the analysis. Externalities exist whenever an actor makes a decision without considering its full consequences to society. For example, a company's financial analysis might not include the full environmental costs caused by the company's activities, which means that such analysis can show profoundly different results than a CBA (see e.g. Boardman et al., 2018 Ch. 1). A fully quantitative CBA typically require monetisation of services provided by nature that are not traded on markets and thus requires use of various economic valuation methods (e.g. the travel cost method, hedonic pricing or contingent valuation, Freeman et al., 2014). Economic valuation of nature is not a panacea in itself and placing an economic value on nature is undoubtedly difficult and uncertain (Tinch et al., 2019), ethically controversial (Hausman et al., 2016; Spangenberg and Settele, 2016) and potentially counter-productive with respect to nature conservation (Gómez-Baggethun and Ruiz-Pérez, 2011). However, some kind of valuation is unavoidable as it is consciously (or unconsciously) done on a daily basis whenever politicians, governmental agencies, municipalities, businesses and individuals make decisions. In practice, decisions on various projects are often based on financial values, including those attached to nature's resources, which do not necessarily reflect their total economic value. Explicit economic valuation of services provided by nature can therefore contribute to increased transparency and more informed trade-offs (Freeman et al., 2014). Systematically mapping effects on the supply of geosystem services and translating them into costs and benefits can thus provide additional information to decision-makers and support more informed decisions about subsurface resource use

1.2. Aim and scope

The overall aim of this study is to investigate the use of geosystem services for a systematic mapping of the effects of subsurface projects, and how this can contribute to a more complete assessment and evaluation of projects regarding their effects on subsurface resources. In this paper we (1) illustrate a systematic mapping of effects on geosystem services using a process-oriented perspective in two conceptual cases representing two common subsurface use projects; (2) translate the mapped effects into costs and benefits items associated with the two projects in a qualitative CBA context to indicate what types of costs and benefits need to be subject to economic valuation; and (3) systematically review economic valuation studies that have targeted changes in the supply of geosystem services to investigate the available support for such valuation. Finally, the general applicability of systematic mapping of effects on geosystem services is discussed, as well as the limitations of using CBA for supporting decisions on subsurface use.

2. Description of conceptual cases

Two conceptual cases have been chosen to represent common conflicts of interest that arise due to subsurface projects in a geological context with an ancient bedrock and quaternary deposits on top, fully or partly below the former Holocene highest shoreline. Such terrains are common in for example Fennoscandia, Canada, and Greenland. Case 1 considers the construction of a tunnel through a fractured crystalline rock, and case 2 considers future exploitation of a glaciofluvial delta deposit for natural sand and gravel extraction (Fig. 1). These projects are drivers of, primarily abiotic, change in a specific geological setting. A geological setting is in this paper defined as the geological, geomorphological, hydrological and climatic conditions of an area including the active processes (thermal, hydraulic, mechanical, chemical and biological) that take place in this environment.

Case 1. Construction of a new tunnel through fractured crystalline bedrock

The first case considers the construction of a four-lane road in a bedrock tunnel. The tunnel will reduce the transport length and thus reduce both travel time and traffic emissions in comparison to the reference, i.e., the current road above ground. Locating road and rail tunnels below ground can result in many benefits, e.g., reduced barrier effects on wildlife and humans, freeing space for development on the surface, reduced travel time, reduced air pollution, and reduced noise pollution (Anciaes and Jones, 2020; Ayalon et al., 2016; Cowie et al., 2012; Forman and Alexander, 1998; Rico et al., 2007). However, construction under the ground surface and below the groundwater table may cause a groundwater lowering which subsequently can give rise to a wide variety of risks and loss of services.

The planned tunnel is located in a typical southwestern Swedish geological setting with a landscape characterised by bedrock hills and a clay-filled valley. Shallow thin till layers, peat bogs and small lakes are scattered across the otherwise bare bedrock. The valley is sparsely inhabited and is mostly covered with forest, agricultural land and pastures. Some of these forests and pastures have high nature values. A

[1] For convenience, "goods and services" are abbreviated to "services" in the rest of this paper.

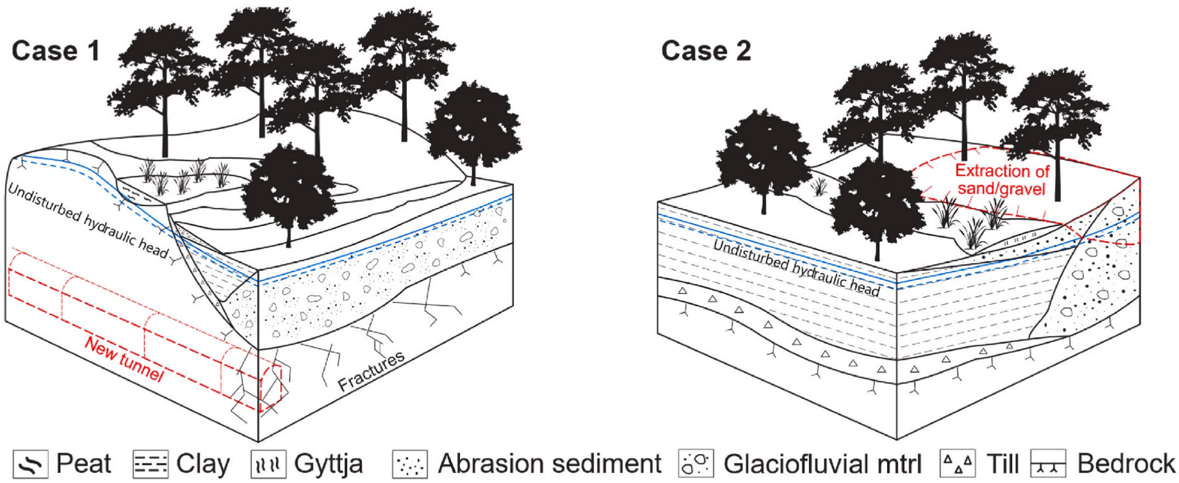


Fig. 1. Illustration of the two conceptual cases and schematic cross-sections of parts of the geological settings. Case 1 refers to the construction of a new tunnel through fractured crystalline bedrock. Case 2 refers to the extraction of geomaterials from a glaciofluvial delta deposit. The subsurface projects are marked in red. The undisturbed hydraulic head is marked with blue.

stream runs through the valley and has eroded the upper soil layers, resulting in a ravine. Springs are present in several places at the edges of the stream, indicating a gaining stream. The highest points of the bedrock surrounding the valley form the boundary conditions for the watershed of the stream. The stream has a trout population and is an important location for breeding/reproduction. The groundwater is used for private consumption, both as drinking water and can affect the efficiency of adjacent ground-source heat pump systems. There may be archaeological remnants in the soil.

The stratigraphy in the valley (from the bottom up) constitutes fractured granitic gneiss with low sulphide content, with one major brittle deformation zone that coincides with the deepest part of the valley. The deformation zone is characterised by its content of crushed rock with a high hydraulic conductivity. On top of the bedrock, there is a layer of till with varying thickness. The deepest part of the valley also has a glaciofluvial deposit that is mainly covered with clay but enters the ground surface in parts of the valley (Fig. 1). The till and thus the main part of the glaciofluvial deposit constitutes confined aquifers. The lower aquifer is recharged where the glaciofluvial deposit is unconfined with additional contributions from the surrounding till and rock aquifers. The aquiclude consists of glacial marine clay with a varying thickness of up to 20 m in the deepest part of the valley. The clay is sensitive to subsidence and a pressure reduction in the lower aquifer may cause a pore pressure reduction and increased effective stress which subsequently may result in subsidence. On top of the clay, there are bodies with abrasion sediments (sand) with varying thicknesses up to a few meters. The abrasion sediment constitutes unconfined aquifers with hydraulic connection to the till at the valley slopes in conjunction with the bedrock outcrops and at the unconfined part of the glaciofluvial deposit. In summary, three aquifers are present in the area: 1) the fractured bedrock, 2) the partly confined till and glaciofluvial material, and 3) the sandy abrasion sediment. The hydraulic connection between the aquifers implies that leakage of groundwater into the tunnel can cause a groundwater pressure drawdown in all three aquifers. The relatively small watershed constituting the valley also implicates boundary conditions that would fail to counteract such drawdown fully. The tunnel is located at a depth of 60 m below the highest bedrock outcrop of the area and approximately 15 m below the valley floor which will result in a high hydraulic gradient towards the tunnel. The conductive fracture zone may also constitute a difficulty regarding sealing the tunnel with grouting, suggesting that a costly watertight concrete lining would be necessary to reduce the leakage sufficiently.

Case 2. Extraction of geomaterials from a glaciofluvial delta deposit

The second case considers the future exploitation of a glaciofluvial delta deposit for geomaterial extraction, as natural sand and gravel are resources having a market value. The reference is to keep the deposit as it is and thus preserve its potential as a future drinking water supply. Glaciofluvial deposits are well-known features throughout Scandinavia and provide valuable geomaterials but can also be important aquifers for drinking water supply, either as a natural source or enhanced by artificial infiltration. In the future, the aquifer in the case may be interesting as a municipal drinking water reserve supply. The municipality faces higher demands on having resilient drinking water systems due to a higher awareness in society about the more uncertain precipitation patterns resulting from climate change, but also regarding other types of security threats.

The extraction of sand and gravel is planned to take place primarily above the groundwater table, but potentially also below the groundwater table depending on issued permits. The removal of material can subsequently result in a wide variety of consequences. The area in question is rural and sparsely densified with some houses and agricultural properties. The few properties located on top of the glaciofluvial formation use groundwater as drinking water by extraction using private wells. The vegetation on the formation mainly constitutes a pine tree forest with herbs and bushes that thrive in the nutrient-poor soil. These kinds of formations have historically been inhabited by humans and have attractive features for establishing transport routes. This implies that there may be archaeological remnants in the soil. The undisturbed system currently discharges groundwater into nearby surface water systems, specifically a wetland, adjacent to the formation and provides a typical landscape (geomorphology) and a specific habitat with the formation itself and the sandy, well-drained soil.

The stratigraphy in the area (from the bottom up) constitutes a relatively flat crystalline bedrock basement covered with a thin layer of till with superimposed post-glacial sediments (Fig. 1). The glaciofluvial delta formation is located directly on top of the bedrock and contains well-sorted sand and gravel. The sand and gravel material has a high ability to store and transmit groundwater, which is naturally protected by a relatively thick unsaturated zone where percolating water is filtered and subject to bio-geochemical processes on its way downward to the groundwater surface. The water turnover in the saturated groundwater zone is part of the hydrological cycle and depends on i) the climate and weather situation, ii) the interaction with biotic habitats as well as on iii) the hydraulic properties, which in turn depend on the geological conditions. The formation mainly constitutes an unconfined aquifer, but parts are covered with clay which makes these parts of the aquifer confined. The clay is prone to subside if the groundwater pressure head in the underlying aquifer is lowered. On top of the clay and in areas where the glaciofluvial delta formation is present at the ground surface, abrasion sediment of sand is present on top of the clay with varying thickness up to a few meters.

3. Method

3.1. Systematic mapping of effects

The systematic mapping of effects on geosystem services due to subsurface projects is based on a gross list of 39 geosystem services, identified by Lundin Frisk et al. (2022) through a systematic literature review. A selection of geosystem services that are of particular relevance to subsurface planning was suggested by Lundin Frisk et al. (2022) and this selection constitutes the basis for the list of geosystem services that is used for the systematic mapping in this study. However, some of the services have been merged or reformulated to avoid having overlapping services (e.g., regulation of mass movements and regulation of erosion were merged).

Our next point of departure is that the provision of geosystem services (G) and ecosystem services (E) is dependent on nature's abiotic and biotic structures and processes. Subsurface (and surface) projects will impact the geological (and geomorphological) structures that are present, and the processes that occur, in the subsurface. To understand the impacts of projects, a good knowledge of this complex system is required, as typically, the processes - thermal, hydraulic, mechanical, chemical, and biological – are coupled. For example, to describe the impacts of a lowering of a groundwater table, the hydraulic-mechanical coupling will impact effects related to soil subsidence and the thermal-hydraulic-chemical-biological coupling will impact the physical and chemical changes in groundwater quality. For each of the geosystem services listed, the effects of the conceptual projects are qualitatively described from a process-oriented perspective: effects on, and interactions between, thermal, hydraulic, mechanical, chemical, and partly biological processes. Their impacts are described qualitatively as negative (−), positive (+), either positive or negative or both (±), or no effects (0).

In this study, we pay particular attention to the impact of a subsurface project on subsurface structures and processes (Δ_{sub}) and how this impact causes changes in the provision of geosystem services (ΔG) and ecosystem services (ΔE). A subsurface project may also have direct biotic impacts on the surface by, e.g., removing a vegetational cover and thus directly influencing the provision of ecosystem services, but such impacts are not the primary focus of this paper. The cascade model (Potschin-Young et al., 2018; Potschin and Haines-Young, 2011) was developed to "explain how the notion of ecosystem services can be used to understand the relationships between people and nature" (Potschin-Young et al., 2018; Potschin and Haines-Young, 2016), and is here adapted to focus on structures and processes in the subsurface and to also include geosystem services (Fig. 2). The subsurface structures and processes and the various functions of the subsurface these give rise to are called intermediate or supporting services when they serve as an input to the provision of final (ecosystem or geosystem) services, available for human use and giving rise to benefits associated with instrumental values in the social and economic system. Some of these values are economic and thus relevant in a CBA context, but there are also other types of instrumental values such as supporting the right to good health (see e.g. IPBES, 2022). The presence of various benefits with associated values might in turn serve as a motivation for initiating or modifying subsurface projects (Fig. 2).

3.2. Translation of effects into a qualitative CBA context

The mapping outlined in the previous section is used as a basis for translating the negative (−) and positive (+) effects on the supply of services caused by the two projects into, respectively, cost and benefit items in a qualitative CBA context. By describing the effects these two projects cause in a qualitative CBA context, the effects on the different services as well as their interconnections are highlighted. This allows for an improved basis for decisions – making the trade-offs of geosystem service loss, depreciation or degradation in return for net gains explicit on the society-wide level. The CBA context enables a comparison of the benefits of a project to its costs, where benefits and costs are assessed in comparison to a reference alternative such as the *status quo*. Both costs and benefits are expressed in monetary units whenever it is practically possible and summarised into a net present value (NPV) where the time perspective is handled by discounting. A positive NPV implies that a project is profitable from a societal perspective (i.e., benefits outweigh costs), a negative NPV is indicative of the opposite. Following mainstream CBA theory as presented by Johansson and Kriström (2016, 2018) and first focusing on services having a market price, the project's NPV can in practice be evaluated as[2]

$$NPV = p\Delta x^s - \Delta C \quad (1)$$

where p is a vector with present values of producer prices of market services, Δx^s is a vector with the changes in supplied quantities of market services caused by a project, and ΔC is the present value change in total costs because of the project.[3]

The project's impact on non-market services (S), i.e., those that are not subject to trade at any market and therefore lack market prices, is economically valued through the associated willingness to pay (WTP) or willingness to accept compensation (WTA), i.e. monetary measures of consumer surplus (Freeman et al., 2014). To also consider this impact, Equation (1) is extended to:

$$NPV = p\Delta x^s - \Delta C + w\Delta S \quad (2)$$

where ΔS is a vector with the changes in available quantities of non-market services caused by the project and w is a vector with present values of WTP or WTA per unit for these changes. Thus, $w\Delta S$ is a monetised measure of the benefit (cost) of an increased (decreased) provision of S. For assessing subsurface projects, the vector S in Eq. (2) includes geosystem services (G) and ecosystem services (E) to the extent that they are non-market services; they are already accounted for in Eq. (1) in cases when they are subject to trade at markets. Apart from these services, there are also other types of non-market services included in S, e.g., human health aspects.

We can now express the focus of our study more precisely in a CBA context. We want to transfer the mapped effects of impact on subsurface structures and processes Δ_{sub} (see Section 3.1) to benefit and cost items reflected by Eq. (2). For non-market geosystem services and ecosystem services, these items are measured as $w_G\Delta G$ and $w_E\Delta E$. One crucial part of this transfer is to prevent double counting by identifying the final impact on human well-being. This involves distinguishing between intermediate services and final geosystem (or ecosystem) services, which might be context-dependent: one particular service might in some contexts be an intermediate one and in other contexts a final one. Only positive (+) and negative (−) effects on final services qualify as benefit and cost items, respectively, in a CBA. Special attention in this respect should be paid to the geosystem services that so far have been classified as supporting services (Lundin Frisk et al., 2022), considering that "supporting ecosystem services" *sensu* Millennium Ecosystem Assessment, 2005 are avoided in recent ecosystem service typologies such as CICES (Haines-Young and Potschin-Young, 2018) because all such services tend to be intermediate ones only (e.g. Jax, 2016; Potschin and

[2] The project is assumed to be "small" in the sense that it has no or only a marginal impact on market prices in the economy.

[3] If the project also affects the government's revenues and expenditures, a term for this impact should be added to Eqs. (1) and (2), see Johansson and Kriström (2016, 2018).

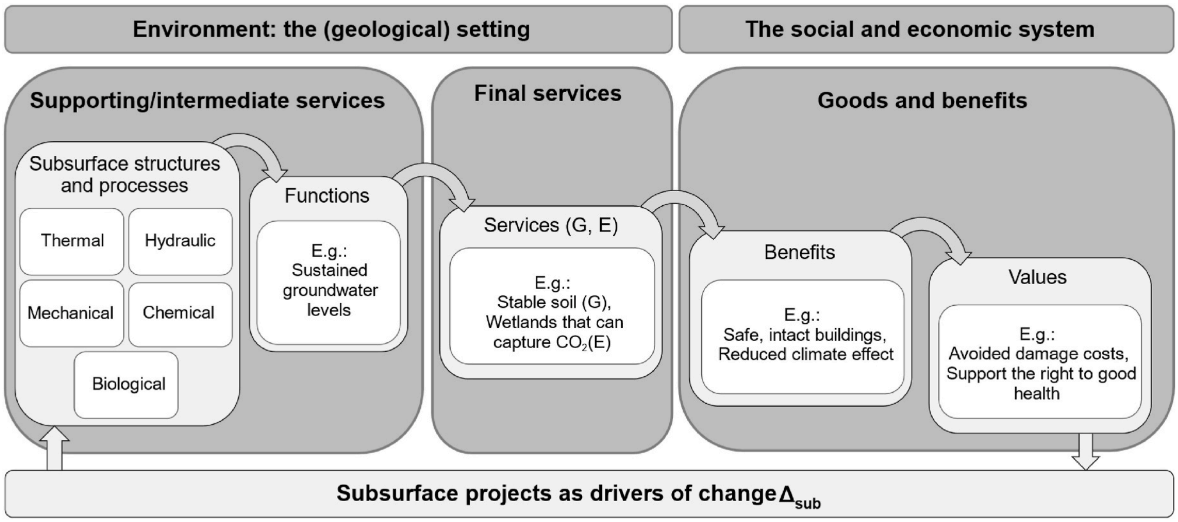


Fig. 2. The cascade model from Potschin-Young et al. (2018), adapted to focus on services derived from subsurface structures and processes and introducing subsurface projects as drivers of change. G: geosystem service. E: ecosystem service.

Haines-Young, 2016).

3.3. Literature review of valuation studies

The systematic review has targeted peer-reviewed articles using mainstream environmental economics to, in monetary terms, value changes in the provision of non-market geosystem services and ecosystem services caused by changes in abiotic structures and processes of the subsurface (e.g., sand extraction from a glaciofluvial delta deposit). Referring to Section 3.2, the review thus includes studies which have applied various non-market valuation methods for estimating $w_G\Delta G$ and $w_E\Delta E$, where ΔG and ΔE are a result of changes to the subsurface (Δ_{sub}). The review was made broader than just focusing on geosystem services relevant to the conceptual cases to investigate the availability of economic valuation studies of geosystem services in general. Studies valuing effects on both geosystem services and ecosystem services due to an abiotic change were included in the review as it is difficult (and perhaps unjustified) in some cases to separate the services from each other. For example, constructing a tunnel in fractured crystalline rock can cause groundwater head drawdown which in turn can cause soil subsidence and affect groundwater-dependent ecosystems, thus causing loss of both geosystem services and ecosystem services.

The literature search was carried out during early to mid 2022 following a modified version of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Moher et al., 2009). The protocol was modified to accommodate that a single researcher instead of two independent researchers carried out the study selection and data extraction. Parts of the PRISMA statement such as sensitivity analyses and certainty assessments are not applicable and were therefore omitted in this study. Peer-reviewed articles and conference papers that meet the criteria outlined Table 1 in their title, abstract or keywords were considered eligible for this study. The Scopus database was used and only texts written in English were included in the searches. For an overview of the search process, see Fig. 3.

To avoid multiple duplicates for each search, the list of geosystem services from Lundin Frisk et al. (2022) was sorted into seven larger groups of presumably overlapping resources: A) Stable and safe environment, B) Groundwater, C) Underground space, D) Underground geomaterials and non-renewable energy resources, E) Renewable underground energy resources, F) Underground cultural heritage repository and G) Other. Each group was searched for independently using targeted keywords, followed by a generic search string related to common economic valuation terms and methods (Appendix B, Table B1). The targeted keywords match terms and expressions commonly used for these resources. However, broader standalone search terms such as “erosion” or “groundwater” were avoided as these returned unmanageable numbers of hits.

Table 1
Criteria used in the systematic review for screening and assessing eligibility.

Inclusion criteria during screening	Exclusion criteria during eligibility assessment
I. Peer-reviewed original research article, conference paper or systematic review. II. Focus on services that can be categorised as either geosystem services orecosystem services. III. Changes in the provision of above said services are driven by changes in abiotic structures and processes of the subsurface. IV. Oriented towards an environmental economic approach and/or CBA. V. Effects on the society or environment are monetised. VI. Focus on non-market services derived from the subsurface. VII. VII. Written in English. VIII. Abstract available.	i. Study not reporting original data or case study. ii. Not presenting details of methodology and results. iii. No full-text available.

For each group, a first sorting of removing duplicates and records without author(s), such as texts related to errata, corrigenda or summaries of conferences, was carried out. After screening the title, abstract and keywords of the remaining records in each group, items that contained the search terms but were unrelated to geosystem/ecosystem services or natural capital/resources/assets were identified and removed. This is because some words and phrases, e.g., ‘erosion’ and ‘mining’, are used across a wide range of contexts of which some are not related to the aim of this study (e.g., ‘data mining’). In total, 71 records matched the eligibility criteria and were thus included in the review (for a list of reviewed articles, see Appendix C).

4. Result

4.1. Effects of subsurface projects on geosystem services

The results of the systematic mapping of potential effects of the two conceptual cases of subsurface use on geosystem services are presented

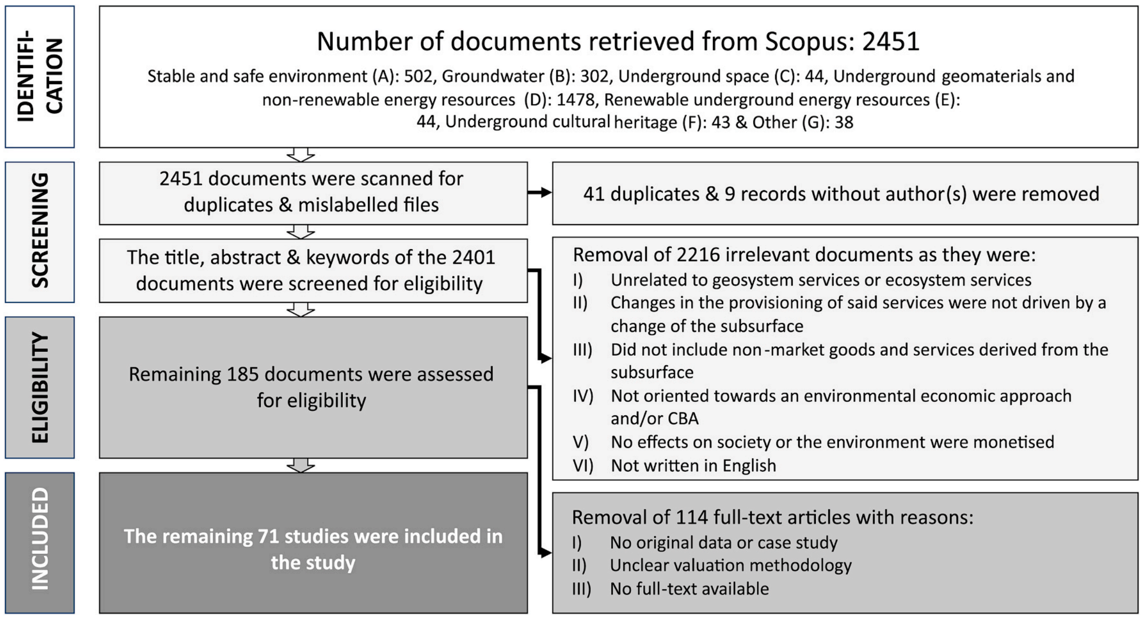


Fig. 3. PRISMA flow diagram showing an overview of the search process and its results.

in detail in Appendix A, Table A1, and summarised in Table 2. The list of subsurface geosystem services is presented in the first column and the qualitative descriptions of the effects are included in the table to provide more details regarding the reasoning.

4.2. *Translation of effects into cost and benefit items*

Based on the generic CBA rule (Eq. (2)), Table 3 summarises all benefit and cost items associated with the two cases. It includes the effects on geosystem services as identified in the systematic mapping (Table 2) but also other types of cost and benefit items which are relevant for the two considered subsurface projects. While there are some common items for the cases, there are also differences such as benefit items of Case 1 associated with the creation of a more efficient traffic solution. Extraction of geomaterials (i.e., a geosystem service typically having a market price) is a common benefit item for the cases, but it reflects the main purpose of Case 2 and a side-effect in Case 1.

While Table 3 is most detailed with regard to benefits and costs due to the impacts on geosystem services identified in Table 2, other benefits and costs associated with the cases are also identified, such as improved transportation by the new tunnel in Case 1 (item B1 in Table 3), and the investment costs in both cases (C1). An integral part of identifying costs and benefits is to avoid the risk of double counting. This is indicated in Table 3 by three examples. First, some geosystem services (just like some ecosystem services) might be intermediate in the production of a final service: Both cases imply a decreased capacity to regulate groundwater quantity and quality (C6 and C7), but this is in turn likely to result in a decreased access to groundwater for extraction (C12) and have a negative impact on services provided by groundwater-dependent ecosystems (C15). Monetised estimates of C12 and C15 are thus likely to include C6 and C7. Second, the benefits of utilising underground space (B7) through a tunnel are accounted for by benefits related to avoiding having a road on the ground surface, both in terms of benefits related to the traffic and to new land use opportunities (B1–B6). Third, some potentially negative impacts on geosystem services might be fully or partly prevented through measures whose costs are included in the investment costs or operation and maintenance costs (C1). This is assumed to be the case in full for the decreased capacity to regulate erosion and mass movements (C5), but only partly or potentially not at all for the other geosystem services. Taking due care to such double counting issues belongs to the nitty-gritty of CBA, and more examples related to the cases are possible though not illustrated in Table 3.

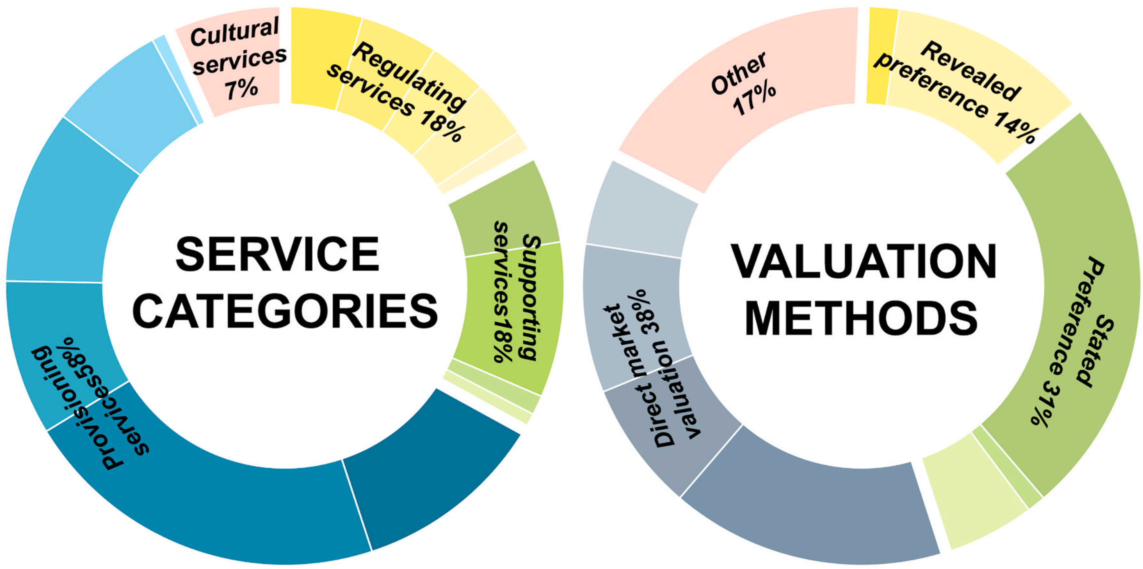
Table 3 also indicates what term(s) in Eq. (2) is likely to provide information about each cost and benefit item. That is, is an item about the impact on a market service for which there is a market price? Or does it (also) require information about one or several non-market services whose economic values have to be estimated through applying one or several of the valuation methods identified in the review in Section 3.3? The high level of aggregation in the items implies that many of the items contain market services as well as non-market services. For example, the benefits of improved traffic safety (B2) in Case 1 are both about reduced damage risks for vehicles and reduced morbidity and mortality risks. While some aspects of these risks are subject to trade at a market, other aspects are about non-market services. For example, while there is a

Table 2
Inventory of effects on geosystem services due to changes in the subsurface for the two conceptual cases. The impacts are described qualitatively as negative (−), positive (+), either positive or negative or both (±), or no effects (0). For detailed descriptions of the effects, see Appendix A, Table A1.

	Geosystem services	Effects Case 1	Effects Case 2
REGULATING SERVICES	Regulation of erosion & mass movements	−	−
	Regulation of water quantity	−	−
	Regulation of water quality	−	−
	Regulation of temperature by underground thermal storage capacity	−	−
	Regulation of soil and bedrock chemistry	0	0
SUPPORTING SERVICES	Stable platform to build on and within	−	−
	Underground space	+/−	0
	Disposal and storage	0	0
	Subsurface habitats	−	−
PROVISIONING SERVICES	Groundwater resources for drinking and as a material	−	−
	Extraction of geomaterials	+	+
	Fossil energy resources	0	0
	Geothermal energy	0	0
CULTURAL SERVICES	Historical, recreational and sacred sites	+/−	−
	Geoscientific and geoeducational resources	+/−	+/−

Table 3
Benefit and cost items in a CBA of Case 1 and Case 2, respectively. GS indicates items which imply a change in the provision of geosystem services. For each item, a checkmark denotes in which NPV term(s) in Eq. (2) the item is likely to be found. Note that the check marks are only indicative, see text.

<table>
<tr><th rowspan="2">Item</th><th>Case 1</th><th>Case 2</th><th rowspan="2">Market services included in $p\Delta x^s$ or ΔC</th><th rowspan="2">Non-market services included in $w_G\Delta G(\Delta_{sub})$</th><th rowspan="2">Non-market services included in $w_E\Delta E(\Delta_{sub})$</th><th rowspan="2">Other non-market services</th></tr>
<tr><th colspan="2">Benefits</th></tr>
<tr><td>B1</td><td>Improved transportation, e.g., reduced travel time and transport costs</td><td></td><td>✓</td><td></td><td></td><td>✓</td></tr>
<tr><td>B2</td><td>Improved traffic safety, e.g., reduced damage risks for vehicles and reduced morbidity and mortality risks</td><td></td><td>✓</td><td></td><td></td><td>✓</td></tr>
<tr><td>B3</td><td>Decreased barrier effects above ground, e.g., improved mobility opportunities for humans and wildlife</td><td></td><td>✓</td><td></td><td></td><td>✓</td></tr>
<tr><td>B4</td><td>Improved health and environment due to reduced noise and decreased air emissions</td><td></td><td></td><td></td><td></td><td>✓</td></tr>
<tr><td>B5</td><td>Increased global climate regulation by reduction of GHG concentrations</td><td></td><td></td><td></td><td></td><td>✓</td></tr>
<tr><td>B6</td><td>Increased access to space above ground</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>B7 (GS)</td><td>Increased access to underground space</td><td></td><td colspan="4">Assumed to be valued through items B1–B6</td></tr>
<tr><td>B8 (GS)</td><td colspan="2">Revenues from the extraction of geomaterials</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>B9 (GS)</td><td>Gain of, or positive influence on, historical, recreational, and sacred sites</td><td></td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>B10 (GS)</td><td colspan="2">Gain of, or positive influence on, geoscientific and geoeducational resources</td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>B11</td><td colspan="2">Potential agglomeration economies, e.g., increased synergy opportunities for other actors</td><td>✓</td><td></td><td></td><td>✓</td></tr>
<tr><td>C1</td><td colspan="2">Construction costs and other investment costs, and operation & maintenance (O&M) costs</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>C2</td><td></td><td>Closure costs</td><td>✓</td><td></td><td></td><td></td></tr>
<tr><td>C3</td><td colspan="2">Reduced traffic safety b/c of transportation due to construction and/or O&M, e.g., increased damage risks for vehicles and increased morbidity and mortality risks</td><td>✓</td><td></td><td></td><td>✓</td></tr>
<tr><td>C4</td><td colspan="2">Impaired health and/or environment due to construction and/or O&M but not through impacts on geosystem services, e.g., noise, dust, air emissions</td><td></td><td></td><td></td><td>✓</td></tr>
<tr><td>C5 (GS)</td><td colspan="2">Decreased capacity to regulate erosion and mass movements</td><td colspan="4">Assumed to be valued through item C1</td></tr>
<tr><td>C6 (GS)</td><td colspan="2">Decreased capacity to regulate water quantity</td><td colspan="4">Assumed to be valued through items C12 and C15</td></tr>
<tr><td>C7 (GS)</td><td colspan="2">Decreased capacity to regulate water quality</td><td colspan="4">Assumed to be valued through items C12 and C15</td></tr>
<tr><td>C8 (GS)</td><td colspan="2">Decreased capacity to regulate temperature by underground thermal storage</td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>C9 (GS)</td><td colspan="2">Decreased access to stable platform to build on and within</td><td>✓</td><td>✓</td><td></td><td>✓</td></tr>
<tr><td>C10 (GS)</td><td>Decreased access to underground space</td><td></td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>C11 (GS)</td><td colspan="2">Loss of or negative influence on subsurface habitats</td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>C12 (GS)</td><td colspan="2">Decreased access to groundwater for current and/or future extraction for drinking water or other purposes</td><td>✓</td><td>✓</td><td></td><td></td></tr>
<tr><td>C13 (GS)</td><td colspan="2">Loss of, or negative influence on, historical, recreational, and sacred sites</td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>C14 (GS)</td><td colspan="2">Loss of, or negative influence on, geoscientific and geoeducational resources</td><td></td><td>✓</td><td></td><td></td></tr>
<tr><td>C15</td><td colspan="2">Negative influence on ecosystem services in groundwater-dependent ecosystems, e.g., bioproduction capacity, recreational opportunities, capacity to capture CO_2</td><td>✓</td><td></td><td>✓</td><td></td></tr>
<tr><td>C16</td><td colspan="2">Decreased existence values and other non-use values associated with affected nature, e.g., biodiversity and geodiversity</td><td></td><td>✓</td><td>✓</td><td></td></tr>
</table>



Group	Service	No.
Regulating services	Regulation of erosion	4
	Regulation of mass movements	4
	Regulation of water quality	3
	Regulation of water quantity	3
	Regulation of temperature by the subsurface	0
	Regulation of soil and bedrock chemistry	1
Supporting Services	Stable platform	5
	Underground space	8
	Disposal and storage	1
	Subsurface habitat	1
Provisioning Services	Groundwater for drinking	10
	Groundwater as a material	19
	Industrial minerals	0
	Nutritional minerals	0
	Construction materials	6
	Metals and other ores	7
	Ornamental materials	0
	Non-renewable energy	6
	Geothermal energy	1
Cultural services	Iconic sites	6
	Sacred and historical sites	0
	History and evolution of Earth	0
	Educational resource	0

Group	Valuation method	No.
Revealed Preference	Travel Cost (TC)	2
	Hedonic Pricing (HP)	11
Stated preference	Contingent Valuation (CV)	23
	Choice Modelling (CM)	1
	Choice Experiment (CE)	4
Direct market Valuation	Replacement Cost (RC)	16
	Production Function (PF)	6
	Market Price (MP)	8
	Damage Cost Avoided (DCA)	5
Other	Benefit Transfer (BT)	16

Fig. 4. Illustration of search results from the systematic literature review. The left figure shows the number of valuation studies per service. The right figure shows the number of valuation methods applied to assess said services.

market for car repairs, you cannot buy a personal traffic mortality risk reduction at a market. However, it might be possible to infer something about how reduced mortality risks are economically valued from behaviour at related markets, such as individuals' willingness to pay for cars with high safety performance, but this is about using valuation methods for finding implicit prices of non-market aspects.

A more detailed description of the items might allow an unequivocal sorting into market services and non-market services, but this is avoided here for the sake of providing an overview with the main message that a CBA of the two cases might provide a biased result if values of non-market services are not included. This is not least true for the benefits and costs associated with impact on geosystem services. As indicated in the table, some geosystem services are used for commodities being traded at a market. A clear example is access to geomaterials, whose extraction typically gives rise to market services such as sand and gravel (B8). A less clear example is access to groundwater (C12), whose extraction results in drinking water and other services for which there might be markets, but not necessarily so because of regulations. Other geosystem services are likely to solely be about non-market services, such as the influence on historical, recreational, and sacred sites (B9, C13). While there might always be exceptions and the check marks in Table 3 are only indicative, one can thus not expect that information from transactions of market services would give full information for a CBA of the two cases.

4.3. Review of economic valuation studies

The result of the literature review shows that relatively few economic valuation studies (71 in total) have monetised changes in the supply of non-market geosystem services [$\Delta G(\Delta_{sub})$] and ecosystem services [$\Delta E(\Delta_{sub})$] due to changes of the subsurface. Furthermore, some services have gained more attention than others with 58% (49 out of 85, as some studies have valued multiple services and are counted separately) of the studies relating to provisioning services (mainly extraction of groundwater and geomaterials and associated benefits or costs). On the other hand, only 7% (6 out of 85) of the studies focused on cultural and supporting services (Fig. 4). From the reviewed literature it is evident that biotic and abiotic structures and processes generally interact to provide beneficial services. Of the studies, 63% (45 out of 71) focus on the valuation of geosystem services [$\Delta G(\Delta_{sub})$], and 37% (26 out of 85) focus on changes to ecosystem services [$\Delta E(\Delta_{sub})$] as a result from a change in the subsurface.

The most common monetary valuation approaches in the reviewed studies are direct market and stated preference methods, accounting for 74% (63 out of 85) of the services valued in the reviewed studies. Individually, the most used valuation method is contingent valuation, followed by replacement costs and benefit transfer (for an overview and description of valuation methods, see e.g. Freeman et al., 2014). Sixty-six of seventy-one studies employed a single valuation method (93%), and the remaining five studies employed two or more valuation methods within the same study. While there are relatively few valuation studies, clearly a wide set of valuation methods has been applied to a broad range of services.

We urge the reader to note that the services that have been valued have been given significant monetary values, suggestive of their importance to society. For instance, Hansen and Hellerstein (2007) evaluated the impact of reduced reservoir sedimentation rates across 2111 U.S. watersheds due to soil conservation practices. Their result showed that the lower soil erosion level in 1997, relative to 1982, was shown to have conserved $154 million in reservoir benefits. Another example is the study by Webber et al. (2006) who carried out an economic impact analysis on the Isle of Wight to determine the local economic impacts provided by rocks, fossils, minerals and landforms (described as geodiversity). They found that 39% of the tourists in their survey had visited the Isle of Wight specifically for abiotic sights. This (geo)tourism was estimated to be worth approximately £11 million in the year 2004/2005 and generate £2.6–4.9 million in local income and support between 324 and 441 full-time equivalent local jobs. However, while there is support for the quantification of some specific services, other services have not, or only partially, been valued in the reviewed literature. An individual breakdown of included aspects for each service category highlights important gaps in the valuation literature, as presented in the following subsections.

4.3.1. Regulating services

The regulating services that have been valued in the reviewed literature are often a combination of both geosystem services and ecosystem services. A good example is valuation studies on erosional processes: there are valuation studies that have estimated overall damage costs induced by soil erosion and runoff (e.g. Patault et al., 2021), benefits of reduced reservoir sedimentation (e.g. Hansen and Hellerstein, 2007) and WTP for restoration of coastal erosion prone beaches (e.g. Dribek and Voltaire, 2017; Saengsupavanich, 2019). However, the reviewed literature on erosional costs and benefits tends to focus on ecosystems (e.g. Hopkins et al., 2018) and their regulating capacity rather than on what is labelled as geosystem services in this study. Another example relates to water quantity regulation (flood protection) and water quality regulation, where the reviewed literature also tends to focus on ecosystems (e.g. Acharya and Barbier, 2000; Tapsuwan et al., 2009). A trend for the regulating services in the reviewed literature is that these studies include only meagre descriptions (and by extent valuation attempts) of the geological and/or geomorphological impact on risks and/or delivery of services. For natural hazards such as floods and landslides, there are valuation studies that have estimated overall damage costs (e.g. Lee et al., 2021; Vranken et al., 2013), effects on house pricing adjacent to landslide-prone nature parks (e.g. Kim et al., 2017), and costs and benefits of landslide induced sediment deposition (e.g. Rangsiwanichpong et al., 2019). One study looked at the economic value of managed aquifer recharge (MAR) as a water management tool for restoring groundwater levels from a societal perspective (Damigos et al., 2017).

None of the studies in the reviewed literature directly relates to the regulating services mapped in either of the cases. However, the study by Damigos et al. (2017) on the economic value of MAR could to some extent be used to derive option values in Case 2 (preservation of the glaciofluvial delta deposit as a future drinking water supply), notwithstanding that the delta, in this specific setting, would likely be sufficiently recharged by precipitation or other sources of inflowing water to the aquifer.

4.3.2. Supporting services

Although supporting services are typically not included as final services in environmental economic assessments (e.g. Pascual et al., 2010), there are several geosystem services labelled as supporting services that have been valued (see review by Lundin Frisk et al., 2022). For example, valuations of underground space typically assess the value of positive externalities derived from using underground space in crowded urban areas (Dong et al., 2021; Mavrikos and Kaliampakos, 2021; Qiao et al., 2017). The rationale for these studies is that decisions based solely on a comparison of construction costs tend to penalise underground construction as the additional benefits of placing something underground are not considered (e.g., that valuable surface space can be used for other purposes such as a park, which brings recreational benefits). By contrast, there are fewer studies on negative externalities due to underground space use (such as e.g. Sundell et al., 2019). When mentioned, the studies focus on short-term impacts such as construction-induced noises, air pollution and traffic (see e.g. Dong et al., 2021), but not on long-term negative impacts like for example reduced efficiency for existing and new geo-energy wells or effects related to the irreversibility of underground constructions. However, as the authors concluded in their two-part study on positive (Qiao et al., 2022a) and negative (Qiao et al., 2022b) externalities of underground space use, urban underground use of space often yields positive net benefits and contributes to urban sustainability. The only study related to the quantification of underground storage focused on the negative effects of underground natural gas storage since it presents similar potential risks as natural gas extraction, e.g. ground and surface water contamination and anthropogenic-induced earthquakes (Jellicoe and Delgado, 2015).

The valuation studies that relate to the supporting services could be used to derive non-market values for a project similar to Case 1 (construction of a new tunnel). Economically valued positive externalities include increased access to space above ground (Qiao et al., 2022a), decreased barrier effects above ground with improved mobility opportunities for humans and wildlife (Dong et al., 2021; Qiao et al., 2022a) and improved health and environment due to reduced noise and decreased air emissions (Dong et al., 2021; Qiao et al., 2022a). Negative externalities include the external cost of artificial recharge and other costs related to land subsidence risks (Sundell et al., 2019; Yoo and Perrings, 2017), compensation for loss of efficiency for adjacent geo-energy wells and negative effects on stygo- and troglofauna (Qiao et al., 2022b). Notably, no studies of relevance for Case 2 were found.

4.3.3. Provisioning services

The provisioning services, especially related to groundwater and geomaterial extraction, are the most studied in the reviewed literature. The focus in studies on groundwater can broadly be divided into three categories: (1) the long-term sustainability of groundwater resources which include degradation or loss of a groundwater source, i.e., the aquifer's replacement cost due to over-extraction (e.g. Carrera-Hernández and Gaskin, 2009) or the benefits of ensuring the groundwater quality of an existing aquifer (e.g. Hasler et al., 2007), (2) loss of groundwater dependent ecosystem (e.g. Tapsuwan et al., 2009), and (3) effects on land market prices (e.g. Sampson et al., 2019).

The identified studies on geomaterials can be divided into three broad categories: (i) the economic contribution and environmental cost of domestic supply (Brown et al., 2011; Garrod and Willis, 2000; Sampson et al., 2019) and the cost of importing aggregates from more distant locations (e.g. Jaeger, 2006), (ii) studies on environmental degradation (e.g. Aragón and Rud, 2016; Arendt et al., 2022), and (iii) studies on societal and economic effects due to extraction of minerals, metals and energy rocks (Collins et al., 2012; Damigos and Kaliampakos, 2006; De Valck et al., 2021).

For Case 1, the study on the effects on farmland market prices due to groundwater drawdown (Sampson et al., 2019) is relevant, and studies on the cost of importing aggregates from more distant locations (Jaeger, 2006) could potentially be applicable to estimate beneficial externalities of reusing surplus masses created by the tunnel project, depending on the rock mass quality. For Case 2, there are several studies that can potentially be used to derive estimates on values related to the project, e.g., the economic contribution of domestic supply of geomaterials (Brown et al., 2011; Garrod and Willis, 2000), environmental degradation costs due to extraction of geomaterials (Aragón and Rud, 2016; Arendt et al., 2022; Brown et al., 2011; Garrod and Willis, 2000), societal effects due to extraction of geomaterials (Collins et al., 2012; Damigos and Kaliampakos, 2006; De Valck et al., 2021), cost of importing aggregates from long distances (Jaeger, 2006) and costs of replacing groundwater sources (Hasler et al., 2007; Hérivaux and Grémont, 2019; López-Morales and Mesa-Jurado, 2017; Wei et al., 2007; White et al., 2001).

4.3.4. Cultural services

For cultural services, the main focus in the reviewed literature is on geotourism, which has emerged as an abiotic parallel to ecotourism (although the two often are linked). The most common structures and processes in these studies are the presence of a specific geological or geomorphological feature (labelled as geodiversity, e.g. Gray, 2011). However, cultural services are the least studied in the reviewed literature: only six studies have placed an economic value on these services. Aspects that have been valued include geopark management and conservation (Cheung et al., 2014), WTP for an accredited geo-guided tour (Cheung, 2016), mine reclamation (Lienhoop and Messner, 2009; Mishra et al., 2012) and recreational value of mining heritage (Pérez-Álvarez et al., 2016). None of the studies of cultural services in the reviewed literature relates directly to either of the cases.

5. Discussion

The current study is a conscious simplification of a complex reality to highlight services that tend to be left out from environmental studies and decisions on access to the subsurface and the resources therein. By combining the geosystem services concept with a process-oriented perspective, we show that effects on the supply of goods and services due to impacts from multiple and different types of projects can be systematically mapped for consideration in assessments of proposed future subsurface use. Translating these effects to cost and benefits items in qualitative CBA terms, makes trade-offs visible and can facilitate consideration of these effects in decisions on the subsurface to ensure sustainable subsurface use and management. In the following sections, the general applicability of systematic mapping of effects on geosystem services using a process-oriented perspective is discussed as well as the limitations of using CBA for supporting decisions on subsurface use. A full CBA relies on both quantification of effects and monetisation of the cost and benefit items. The quantification of effects can be made based on more or less advanced methods (simple analytical methods or simplified calculations, more advanced modelling efforts (e.g. Wikby et al., 2024) or expert elicitation (O'Hagan, 2019). Monetisation may require valuation studies to collect primary data, which can be resource-demanding, and the first step is typically to investigate the possibility of transferring valuation results from earlier valuation studies. Hence, the availability of such valuation studies of geosystem services was investigated and the results are further discussed.

5.1. Benefits of systematically mapping effects on geosystem services

The idea of geosystem services is both appealing and challenging. On the one hand, as a general description and categorisation of contributions to human well-being from subsurface resources, it helps to acknowledge otherwise potentially overlooked resources and to raise awareness about them among both subsurface experts and non-experts. On the other hand, as a gross simplification of an interconnected reality, there are limitations similar to the concept of ecosystem services regarding how far it can contribute to a better understanding of complex subsurface processes (e.g. Evans, 2019; Norgaard, 2010). Nevertheless, using the suggested list of subsurface geosystem services from Lundin Frisk et al. (2022) as a basis for systematically mapping the effects of two subsurface projects, combined with a process-oriented perspective, proved to be useful for describing the full range of (negative and positive) effects these projects may have on the future supply of subsurface resources. Although the two considered cases are conceptual, the systematic evaluation of effects was useful for i) better understanding of the various geosystem services themselves by putting them into specific contexts, ii) evaluating the full range of effects on these geosystem services and thus avoiding focusing only on one aspect (e.g., groundwater drawdown), and iii) connecting the identified effects to final services, and consequently to cost and benefit items to be included in a CBA context for subsurface projects. Mapping the effects on geosystem services from subsurface projects, i.e., their identification and description, is also useful in qualitative or semi-quantitative assessments and the process-oriented perspective may help to better unveil a broad range of effects that otherwise could be neglected.

5.2. Including geosystem services within a CBA context

To achieve sustainable use of the subsurface and its resources, and thus contribute to sustainable and resilient communities and cities, it is necessary to make sound strategic decisions on prioritisation of competing geosystem services and resolve potential conflicts of interest. A qualitative CBA as investigated here, is useful, for example, for defining the costs and benefits of a project in a way that avoids double-counting and identifying needs for data on the value of non-market services, whereas a quantitative CBA can be important in a decision-making process to demonstrate that costs of the project do not outweigh its benefits on a society-wide level, i.e., the decision on a particular subsurface use does not lead to social loss.

The two cases clearly illustrate that the two decision situations for the conceptual subsurface projects are associated with effects on both market and non-market services. The two cases thus indicate what is at stake for society as a whole regarding subsurface resources in decisions about tunnel constructions and geomaterial extraction in the geological settings described here. Indeed, in Sweden, the extraction of geomaterials from glaciofluvial deposits has gradually decreased over the past decades as geomaterial from glaciofluvial deposits is replaced with reused or imported material, crushed stone or till (SGU, 2015). However, relocation to more distant locations such as importing geomaterials can introduce other societal costs, such as increased CO_2 emissions and other negative externalities associated with long-distance transportation of these materials as an unintended consequence (Brown et al., 2011; Jaeger, 2006). Although these types of secondary consequences were outside the boundary conditions set in the qualitative CBA conducted in this paper, and thus not included in the analysis, such effects are important to acknowledge.

In a broader perspective, given a full quantification and monetisation of relevant cost and benefits items, the application of a CBA for subsurface projects can provide a solid basis for a decision from a consequentialist view, considering the costs of the project and the changes in supplied quantities of both market and non-market services caused by a project. But indeed, a CBA cannot give more answers than what its theoretical and ethical points of departure allow. For example, the anthropocentric preference satisfaction consequentialism on which CBA relies (Hausman et al., 2016; Perman et al., 2011) can be contrasted to non-consequentialism represented by rights-based ethics and duty ethics, both concerning humans and the environment. Examples related to these contrasts are threefold. Firstly, (1) while a CBA can show how benefits and costs are distributed across groups in society and in this sense provide useful information for a discussion about fairness, a focus on the sign of the net present value could hide outcomes that potentially are viewed as unfair from, for example, an egalitarian point of view. Secondly, (2) the particular fairness issue about future generations, where it is debatable whether the interests of future generations are adequately represented in a CBA "via the concerns of those who are now living for those who will come after them" (Hausman and McPherson, 1996 p.102) and through the use of discounting when computing NPV (see also section 5.3). Thirdly, (3) while nature's instrumental values for human well-being are to be taken into account to the greatest extent possible in a CBA, its anthropocentrism excludes by definition values in nature that are non-instrumental with respect to humans.

Another issue with decisions regarding the subsurface and geosystem services is that the analysis needs to deal with geological or multiple generations' timescales since the structures and processes that provide these services can range from present-day processes (e.g. groundwater recharge) back to features inherited from millions of years ago (e.g. the availability of underground space in crystalline bedrock). Researchers such as van Ree and van Beukering (2016) have highlighted in their papers that decisions regarding the subsurface from a time perspective can be differentiated by several orders of magnitude from decisions on ecosystem services that generally relate to features developed during modern times (i.e. hundreds up to thousands of years). If both are to be included within the same decision framework, the possible temporal difference between some of the services should be acknowledged.

In a CBA, time differentiation raises the question of choosing a suitable approach to calculate the NPV to compare alternatives and scenarios. Over the years, scholars have identified and analysed in detail some of the key shortcomings of CBA as applied to ecosystem services. One of the most critical problems concerns the discount rate one has to apply for CBA to be manageable, on which a consensus has remained elusive for the past few decades. Furthermore, this issue does not seem close to being resolved (see e.g. Parks and Gowdy, 2013; Wegner and Pascual, 2011). High discount rates are assumed by some (e.g. Dominati and Mackay, 2013), whereas others suggest that negative discount rates could be more meaningful (e.g. Hoel and Sterner, 2007), and yet others have suggested positive but decreasing discount rates over time (e.g. Arrow et al., 2014). While this issue tends to be especially manifested in a CBA context because it cannot be avoided in a calculation of a present value of future benefits and costs, the need to handle this time perspective issue is present for all decision-support methods that have to consider future effects, and thus what weight to place on those effects. This is thus a crucial issue for both mono-criterion methods (which assess a given project against a single and specific objective, such as when a CBA only focus on net present value) and multi-criteria methods (which appraise or evaluate a project by taking into account more broadly the various dimensions of interest, such as Multi-criteria Decision Analysis). That said, including geosystem services within a CBA context provides an opportunity to explicitly discuss the time perspective issue with these types of geological features and the services they provide.

Clearly, although we have demonstrated the usefulness of CBA as a method for evaluating the positive and negative effects of subsurface projects, we do not claim that attaching an economic value to natural capital and setting up a CBA is the only, or even, the best way, to allocate scarce resources. Quite the contrary, we acknowledge the need for complementary assessment methods. However, CBA is a method that can contribute to making the overall benefits or cost associated with subsurface exploration explicit and therefore has a critical role to play in heightening the general awareness of the subsurface as well as highlighting the geosystem services supplied by the subsurface and their importance relative to and in combination with other contributors to sustainable human well-being.

5.3. Economic valuation of geosystem services

The request for monetary estimates of the economic value of nonmarket goods and services has steadily increased over the last few decades (Richardson et al., 2015). However, it is not always possible or efficient to conduct an original valuation study for a specific geographic area or service of concern (e.g., due to time and financial limitations). In these cases, secondary data might be used to monetise services by transferring information available from earlier studies already completed in another, but similar, location or context (e.g. Richardson et al., 2015). Economic methods to value non-market services derived from ecosystems are available as a result of several decades of valuation research (Petrolia et al., 2021; Smith, 2006; Tinch et al., 2019) and the literature review shows that these methods have been broadly used to assess the monetary value of geosystem services. Yet, the literature review indicates that there is a scarcity of economic valuation studies that monetise changes in the supply of non-market geosystem services (and ecosystem services) due to changes in subsurface structures and processes. Furthermore, the literature review indicates that out of the services that have been valued, a few services have received most of the attention with 58% of the studies relating to provisioning services (especially services related to provisioning and to some extent regulating of groundwater and activities surrounding extraction of geomaterials). On the other hand, the valuation of cultural geosystem services is typically rare, undermining an understanding of the multifunctionality of the subsurface.

The studies identified in the literature review as relevant for the two conceptual cases span a wide range of services and locations but few, if any, are similar enough in terms of location and context to be readily applicable for benefit transfer to the situations that the two cases represent. In other words, a broad library of valuation studies is often needed for benefit transfer as each site and context are to some extent unique. Support for the economic valuation of geosystem services from both a conceptual perspective and as a basis for benefit transfer is concurrently lacking. By contrast, such databases (e.g. Brander et al., 2023) have been developed to provide robust and easily accessible information on the economic benefits of ecosystems and biodiversity and the costs of their loss. Hence, the cases illustrate that there is a scientific gap regarding valuation studies related to a wide range of services derived from the subsurface. Geosystem services that have received little or no attention in the reviewed literature include the research value of geological records and the role they play in education, and the valuation of effects on subsurface habitats. This gap for these and other geosystem services is problematic since it indicates that parts of the subsurface, and the services it provides, risk being neglected. While the presented cases are conceptual, they represent common conflicts of interest for which conducting a CBA could provide an improved basis for decisions by highlighting the trade-offs of geosystem services loss or degradation in return for net gains. However, setting up a CBA limited to results from available studies in literature rather than primary data could provide a skewed result where some services are emphasized, and other services are undervalued.

Valuing geosystem services economically provides a means of establishing a common framework or reference point between different stakeholders, scientific disciplines and a wider public. For services that often are complex and sometimes intangible, monetisation can function as a communicative tool that allows the economic value of these to be clearly communicated. Parallels can be drawn from the more well-established ecosystem services, where Costanza et al. (1997) and

Sukhdev et al. (2010) showed that economic valuation of ecosystem services can stimulate additional research and debate, increasing their weight in policy decisions. That said, the monetisation of nature is not a panacea in itself and placing an economic value on nature is undoubtedly difficult and uncertain (Tinch et al., 2019), ethically controversial (Hausman et al., 2016; Spangenberg and Settele, 2016) and potentially counter-productive with respect to nature conservation (Gómez-Baggethun and Ruiz-Pérez, 2011). Furthermore, more specifically for the valuation of geosystem services, there are at least three major concerns.

First, an issue with a monetary valuation of geosystem services that is highlighted in this study is that for some services (e.g. regulation of groundwater quality) it is both difficult (and perhaps unwarranted) to separate geosystem services from ecosystem services as these interact to provide beneficial services. This seems to be especially true for the regulating services that were reviewed. The difficulty of separating the two types of services is well-known. For instance, in the paper by Smith et al. (2017), they found that 29 biotic and 11 abiotic features affected the delivery of 13 ecosystem services by systematically reviewing 780 papers. This difficulty in separating the two 'systems' has elicited authors to suggest the use of broader terms such as Natural capital (NC) as a stock that yields a flow of services over time. However, as Gray (2018) has stressed, for these broader terms to capture all of nature, the abiotic nature must be put on par with the biotic parts. Otherwise, there is a risk of undervaluing the abiotic and/or geosystem contributions to human welfare.

Second, the low number of valuation studies impedes efforts to include geosystem services in decision support tools such as CBA and fails to highlight the range of values that are associated with said services. The study by van Ree et al. (2017) suggests that there is more to be done regarding research on geosystem services in general. In this study, they summarised the number of publications between 2000 and 2016 on goods and services from the subsurface (defined as geosystem services by the authors) and showed that for every publication of geosystem services, 140 studies on ecosystem services are published. Clearly, there is a gap here that needs to be filled to capture the full value of nature.

Third, the finiteness of some services (e.g. underground space, geomaterial extraction or groundwater mining) is not thoroughly addressed in the studies included in the review. To illustrate, the subsurface is an important resource, not least in densely populated cities, but it is a limited resource. Unlike structures above ground, underground constructions cannot be reused in the same way through demolition and new construction. An underground construction is largely a permanent intervention, as such, subsurface construction requires to be preceded by careful planning where current and future societal needs are considered. One example could be to predetermine which type of construction should have precedence at a certain depth (e.g. a pedestrian tunnel might have precedence at shallow depths and sewage pipes can be located further down). However, no such attempts to aid the allocation of 3D space based on economic value could be found in the reviewed literature.

Finally, there are potential valuation studies of geosystem services which were not included in the literature search conducted because i) the keywords used in the search strings potentially do not match all possible labels used for the selected geosystem services, ii) the studies are reported in unindexed grey literature, or iii) studies are reported in other languages than English. Indeed, one could expect that some services and the attributes that underpin them are discussed in the grey literature (see e.g. Webber et al., 2006). It should also be kept in mind that market services were not targeted in the literature review. Nonetheless, the review suggests that there are scientific gaps that require efforts to fill if the wide range of geosystem services and associated values are to be included in decision support systems such as CBA. It should also be kept in mind that geosystem services which typically have a market price (such as commercial ores) were not targeted in the literature review and that such market prices might be flawed from a societal point of view because of the presence of externalities (such as those caused by mining).

5.4. Wider implications for the geosystem service concept

Recent contributions to environmental accounting have stressed the need for valuation to focus on final services rather than on intermediate services and ecosystem functions, as this decreases the risk of double counting (Pascual et al., 2010). It has been argued (see e.g. van der Meulen et al., 2016; van Ree and van Beukering, 2016) that some supporting services are related to carrier functions of the geological substrate and thus are directly used to enhance human well-being (i.e., a final service). However, in our conceptual Case 1, the benefits of using underground space for transport infrastructure are expected to be valued, not as a final service itself, but rather as benefits derived from safer transportation, saving space aboveground etc. (items B1 – B6 in Table 3). This indicates that including supporting services (such as space and a stable platform to build upon) as final services in a CBA can imply a risk of double counting. However, every project is unique and what and how each service, primarily amongst the supporting and regulating services, is to be valued must be carefully considered since what is an intermediate and what is a final service may differ between projects. The CBA analyst must therefore always be attentive and aware of this risk.

As concluded by Lundin Frisk et al. (2022), an overview of geosystem services would be desirable and could mimic 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. If geosystem services are to be included in the abiotic extension of CICES, in which supporting services are excluded by definition, it should be further investigated whether the supporting geosystem services should be reclassified so as not to be overlooked in economic valuation and CBA. For example, 'subsurface space and storage' may potentially be reclassified into provisioning services, and 'stable platform to build upon and in' may potentially be reclassified to a regulating service, i.e. the ability of the subsurface to regulate mechanical stress and strain to distribute loads.

6. Conclusion

The main conclusions from this study are listed below.

- Subsurface structures and processes (thermal, hydraulic, mechanical, chemical and biological) are inherently coupled and interact with biotic systems. Using a process-oriented perspective combined with a gross list of geosystem services for mapping of effects of subsurface projects can provide an improved basis for decisions – making the trade-offs of geosystem service loss or degradation in return for net gains explicit on the society-wide level. The theoretical limitations of CBA, however, highlight the need for complementary types of assessments that together might better capture the large diversity of values of nature.
- The literature review reveals that the economic valuation of non-market geosystem services is possible using well-established valuation methods, but studies targeting such economic valuation are scarce, especially those regarding cultural geosystem services.
- Supporting and regulating geosystem services can be either intermediate or final services depending on context. Therefore, if geosystem services are to be included in the abiotic extension of CICES, in which supporting services by definition are excluded, reclassification of the supporting geosystem services should be considered not to risk being overlooked or double-counted in economic valuation and in assessments such as CBA.

CRediT authorship contribution statement

Emrik Lundin-Frisk: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Tore Söderqvist:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Johanna Merisalu:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Yevheniya Volchko:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Lars O. Ericsson:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Jenny Norrman:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

Data will be made available on request.

Appendix A. Inventory of effects on geosystem services due to changes in the subsurface in the two conceptual cases with detailed descriptions

Table A1
Inventory of effects on geosystem services due to changes in the subsurface in the two conceptual cases. The impacts are described qualitatively as negative (−), positive (+), either positive or negative or both (±), or no effects (0).

Geosystem services		Effects Case 1	Description of changes in the supply of services due to Δ_{sub}	Effects Case 2	Description of changes in the supply of services due to Δ_{sub}
			Case 1 - Construction of tunnel through crystalline bedrock		Case 2 - Extraction of geomaterials from glaciofluvial deposit
REGULATING SERVICES	Regulation of erosion & mass movements	−	At the openings of the tunnel, there can be a risk of increased erosional processes and mass movements if the construction is not carried out properly. This can have a negative impact on the road which can result in higher maintenance costs. Should any damages occur, the project owner (or the contractor) will be responsible for any costs.	−	A new activity of extraction of geomaterials at the site will include removal of vegetation, exposing the glaciofluvial material and making the material more vulnerable to erosional processes. Erosional processes and the extraction of material itself may change mechanical conditions in the subsurface and potentially cause mass movements. The owner of the site will be responsible for taking necessary safety measures to prevent any accidents or damages to the surroundings due to the geomaterial extraction. This cost is assumed to be included in the site owner's direct costs.
	Regulation of water quantity	−	Changes to subsurface conditions due to the underground construction can alter the hydraulic pressure in the fractured bedrock and subsequently result in changes in flow patterns and lowered groundwater levels. The magnitude of the groundwater level decreases and the extent of the cone of depression is determined by leakage of groundwater into the tunnel and the transmissivity of the fractured rock. A lowered groundwater level may locally give a decreased capacity of wells and a decreased provision of ecosystem services due to degraded groundwater-dependent ecosystems in wetlands and in hyporheic zones. Any lost capacity of wells must be paid as reimbursement costs by the project owner. The cost for reduction in ecosystem services may be paid by the project owner by putting requirements on the project to invest in measures to reduce the risk of environmental impact from leakage.	−	Removal of glaciofluvial material above the groundwater table will decrease the volume available for temporary storing infiltrating precipitation and regulating stormwater. If the extraction extends below the groundwater table, removal of the glaciofluvial material will also change the flow regime for the groundwater: the groundwater table will be lowered and the turnover time in the aquifer can decrease. The removal of vegetation in itself can also affect the regulation of the groundwater quantity: glaciofluvial material is highly permeable and most precipitation is still likely to infiltrate and percolate, but more water will reach the groundwater table as the evapotranspiration will be less. Changes in the capacity to regulate groundwater quantity can have an impact on the surface water system and thus the wetland where the water discharges. The potential economic effects as a result of a decreased capacity to regulate groundwater quantity are assumed to not be included in the site owner's costs.
	Regulation of water quality	−	The changes in flow patterns due to a leakage of groundwater into the underground construction may cause a degradation of the water quality in the fractured rock. The change in groundwater chemistry can, e.g., be a result of an increase of organic matter from the wetlands that have a hydraulic connection to the fractured rocks, which subsequently can cause a change in redox conditions and pH. These changes in groundwater chemistry can cause a lower water quality in the fractured aquifer which	−	Extraction of geomaterial in the deposit above the groundwater table will decrease the thickness of the unsaturated zone and thus decrease the time for percolating water to reach the groundwater table. Consequently, the deposit's ability to filter and support bio-geochemical processes to provide a stable groundwater temperature and chemistry will decrease. The groundwater resource also becomes more vulnerable to any infiltrating anthropogenic contamination. If the extraction of materials is extended to below the groundwater table, the

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Table A1 (*continued*)

Geosystem services		Effects Case 1	Description of changes in the supply of services due to Δ_{sub} Case 1 - Construction of tunnel through crystalline bedrock	Effects Case 2	Description of changes in the supply of services due to Δ_{sub} Case 2 - Extraction of geomaterials from glaciofluvial deposit
			subsequently can cause, e.g., intensified degradation of cementitious materials, corrosion on steel installations, and drinking water with degraded quality. Constructing the tunnel can also give rise to groundwater contamination from chemical sealing agents or nitrogen from explosives used in the excavation process. This loss of capacity for regulation of groundwater chemistry is assumed not to be included in the project owner's cost. However, any contamination of the groundwater caused by human activity can become a cost to the polluter, regardless of whom. Reduced water quality in wells must be reimbursed by the project owner and increased corrosion of the underground facility will be paid by the project owner as increased maintenance.		groundwater level can potentially be lowered (depending on the extraction method) and the aquifer will become highly vulnerable to contamination. This loss of capacity for regulation of groundwater chemistry is assumed not to be included in the site owner's cost. However, any contamination of the groundwater caused by human activity can become a cost to the polluter, regardless of whom.
	Regulation of temperature by underground thermal storage capacity	–	Construction of the tunnel (and potential lowering of the groundwater table) might affect nearby ground source heat pump systems in the surrounding crystalline rocks. Future opportunities that are lost by occupying the underground space are typically not included in the project owner's cost. Compensation for the decreased efficiency of nearby geo-energy and cost related to this degradation is, however, included in the project owner (or the contractor) costs.	–	The extraction of geomaterial (and potential lowering of the groundwater table) is not likely to affect nearby geo-energy wells in underlying crystalline rocks. However, the future possibility for ATES (Aquifer Thermal Energy Storage) is decreased. The lost future opportunity by the extraction of geomaterial is assumed not to be included in the project owner's cost.
	Regulation of soil and bedrock chemistry	**0**	Not relevant for this case since the granitic gneiss has a low content of sulphides.	**0**	Glaciofluvial material does in general not contain large amounts of easily weathered minerals. A change in groundwater chemistry can potentially affect the redox conditions, but this is not likely to affect the ability to regulate soil and bedrock chemistry.
SUPPORTING SERVICES	Stable platform to build on and within	–	The tunnel is constructed in fractured gneiss, with thick overlaying layers of subsidence-sensitive clays. The gneiss itself is a stable material to build within but the tunnel itself will act as a drainage and lower the hydraulic head of the groundwater in the crystalline rock and subsequently the hydraulic head in the lower confined aquifer in till. This in turn will decrease the pore pressure in the overlaying clay which may lead to subsidence and subsidence damages to the built environment, such as buildings, roads and pipes. The project owner will be responsible for damages and be forced to reimburse the property owners if there is evidence that the tunnel construction has caused the damages.	–	The glaciofluvial material forms a good platform to build on in general. The extraction of geomaterials below the groundwater table, however, will lower the groundwater table and potentially cause decreased pore pressures in nearby clay layers which are in hydraulic contact with the glaciofluvial deposit. This in turn may cause soil subsidence in the soft soil with potential damages to nearby houses, pipes and cables. Damaged buildings and infrastructure give rise to direct costs for reparation/reimbursement but may also give rise to secondary consequences such as health impacts and lowered property values. These costs are assumed to be paid by the project owner if there is evidence that the extraction activity has caused the problem. However, regulations will probably only give permits to such activities that are not likely to affect the surroundings.
	Underground space	+/–	The tunnel will give rise to many benefits such as decreased travel and transportation time, increased traffic safety, decreased barrier effect at the ground surface, improved health due to decreases in air emissions, freeing of land above ground, and decreased GHG emissions. There may however, be conflicts with regards to competition of underground space. Furthermore, when a tunnel is constructed, a permanent cavity (from a human perspective) is created that future generations will inherit. Occupying the space with a tunnel provides benefits for the society. Future opportunities that are lost by occupying the underground space is typically not included in the project owner's cost.	**0**	Even if glaciofluvial deposits are excellent to build on top of, they are less beneficial for underground constructions due to the high hydraulic transmissivity, and thus high groundwater flow and less ability to transmit/distribute forces within the soil/unconsolidated/loose material. In this rural area, it is thus not likely that the formation will be targeted as a location for underground construction. It is rather a competition for the space aboveground that could be an issue. Future opportunities that are lost by removing part of the underground space are typically not included in the project owner's cost.
	Disposal and storage	**0**	Not relevant for this case	**0**	In older times, it was not uncommon to first extract geomaterials and then refill the hole with waste.

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Table A1 (*continued*)

Geosystem services		Effects Case 1	Description of changes in the supply of services due to Δ_{sub} Case 1 - Construction of tunnel through crystalline bedrock	Effects Case 2	Description of changes in the supply of services due to Δ_{sub} Case 2 - Extraction of geomaterials from glaciofluvial deposit
					Within the EU, this is prevented today by regulation. In general, these glaciofluvial deposits are not suitable for disposal of materials that may leach contaminants. It is also not a suitable type of geological formation for other types of storage like carbon or hydrogen storage. Thus, it is not likely to be a conflict for future use.
	Subsurface habitats	−	The leakage of groundwater may cause degraded groundwater-dependent ecosystems that provide habitat for groundwater-dependent flora and fauna. The fractured rock aquifer itself also provides a habitat for stygofauna. The costs of lost habitats and the reduced capacity to regulate water quality and flow are not assumed to be accounted for by the project owner.	−	Extraction of geomaterial in the deposit will destroy the current habitat on top of the formation, which also can contain habitats for burrowing animals such as rabbits, badgers, worms etc. who rely on the soil and sub-soil for their living quarters. Surrounding water systems, including the wetland, will potentially receive less or no water, with less stable base flow, and with an altered water chemistry (and physical parameters). This may affect the habitat for species in the wetland and in other nearby waters, fed by groundwater discharge from the glaciofluvial formation. Finally, there is a fauna in the aquifer itself, whose habitat will be affected, either as a result of changing groundwater chemistry and temperature or as a result of the physical removal of space for this fauna to live in. When a gravel extraction site is closed, the site owner is responsible for the reestablishment of a soil profile and vegetation, thus the top vegetation is likely to be restored over time. The groundwater flow, chemistry and temperature, however, will be permanently altered. Damages to nearby wetlands and species living in the aquifer are not assumed to be accounted for by the project owner.
PROVISIONING SERVICES	Groundwater resources for drinking and as a material (industrial and irrigation purposes)	−	The rock and soil aquifers in the vicinity of the tunnel are used as drinking water. The changed storage capacity due to groundwater lowering and the degraded water quality due to changes in flow patterns may cause a reduction in the potential to extract sufficient amounts of groundwater of good quality. Should existing wells be negatively affected by the tunnel, costs are paid by the responsible party. However, the loss of the option to, in the future, not be able to extract groundwater for drinking water production is not assumed to be paid by the project owner.	−	The capacity and the quality of the water in small household wells situated in the vicinity of the future gravel extraction site are highly dependent on the gravel extraction activity. From a quality perspective, changes may be induced due to altered flow regimes and chemistry, as well as potentially being more vulnerable to anthropogenic contaminating activities. From a quantitative perspective, it will depend on whether the gravel extraction extends below the groundwater table. The reduced storage capacity and the reduced ability to naturally regulate the groundwater chemistry may also make the deposit unsuitable as a future drinking water reserve supply for a larger population. Should existing wells be negatively affected by the gravel extraction industry, costs are assumed to be paid by the responsible party. However, the loss of the option to, in the future, extract groundwater for drinking water production is not assumed to be paid by the project owner.
	Extraction of geomaterials	+	The excavation of the tunnel will result in masses of bedrock that can be used as construction material in other projects. The project owner receives the revenues from selling the masses or the reduction in costs by using the material within the project. In this conceptual case, this is relevant since the granitic gneiss is low in sulphide content.	+	Extraction of glaciofluvial material. The project owner receives the revenues of extraction and pays the extraction costs.
	Fossil energy resources	**0**	This is not relevant to the described geological setting.	**0**	This is not relevant to the described geological setting.
	Geothermal energy	**0**	Construction of the tunnel is not expected to lower the potential for geothermal energy extraction. However, there can be conflicts regarding competition for space.	**0**	In general, the possibility to extract geothermal energy for, e.g., connection to a district heating system is not affected by the extraction of glaciofluvial deposits. The depth to extract geothermal energy in this type of geological setting is far deeper than the Quaternary glaciofluvial formation, and the only conflict could be in terms of the (surface) location of geothermal wells. On the other hand, there may also be synergy effects in terms of infrastructure, should such installation be

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Table A1 (*continued*)

Geosystem services		Effects Case 1	Description of changes in the supply of services due to Δ_{sub}	Effects Case 2	Description of changes in the supply of services due to Δ_{sub}
			Case 1 - Construction of tunnel through crystalline bedrock		Case 2 - Extraction of geomaterials from glaciofluvial deposit
					of interest in the future. Overall, extraction of geothermal energy in this geological setting, in a rural context, is highly unlikely.
CULTURAL SERVICES	Historical, recreational and sacred sites	+/−	Underground construction may damage or degrade sites of historical, recreational, and sacred value. However, the construction may also expose these sites so that they can be visited and/or preserved for the future. Many underground artefacts have been discovered due to underground construction. Depending on the country-specific law, the project owner may be responsible for paying for archaeological investigations.	−	These kinds of glaciofluvial formations have historically been inhabited by humans. This implies that there may be archaeological remnants in the soil. Glaciofluvial deposits are often characteristic features of the landscape and contribute to people's experience of the natural and cultural environment. Geomaterial extraction from these glaciofluvial deposits can thus damage and even destroy sites of historical, recreational, and sacred value. Depending on the country-specific law, the site owner may be responsible for paying archaeological investigations.
	Geoscientific and geoeducational resources	+/−	Geological and geotechnical investigations carried out before and during construction typically increase the general geological knowledge in the area along the tunnel corridor. Furthermore, during construction and afterwards, the tunnel allows access to sites that can have a scientific and/or educational value that have previously been inaccessible. The benefit or the cost is not assumed to affect the project owner.	+/−	Geomaterial extraction from the glaciofluvial deposit can expose the material and provide scientific and educational valuable information. This is a potential synergy if it is made available for this (field investigations and field trips), otherwise the opportunity gets lost. The benefit or the cost is not assumed to affect the site owner.

Appendix B. Overview of keyword combinations applied in the systematic review and resulting hits

Table B1
An overview of search strings used in Scopus for the broad search and corresponding hits. The searches were carried out between 2022-03-13 and 2022-03-17.

Group	Geosystem services	Search string(s) used				
		Terms related to individual geosystem services		Economic terms related to non-market valuation	No. hits	Relevant hits
Stable and safe environment (A)	Regulation of erosion, Regulation of mass movements, Stable platform to build on and within, Regulation of soil and bedrock chemistry	(“land degradation” OR “soil erosion” OR “coastal erosion” OR “cliff erosion” OR “landslide*” OR “mass movement*” OR “mass wasting*” OR “earthflow*” OR “rock fall*” OR “rock slide*” OR “soil creep” OR “debris flow*” OR “mudflow*” OR “avalanche*” OR “soil slip*” OR “slope movement*” OR “expansive soil*” OR “soil creep” OR “subsidence” OR “sinkhole”)	AND	(“economic valuation*” OR “monetary valuation*“ OR “market valuation*“ OR “revealed preference*” OR “stated preference*” OR “valuation techniq*” OR “damage cost*” OR “mitigation cost*” OR “total economic value*” OR “hedonic price*” OR “hedonic value*” OR “replacement cost*” OR “contingent valuation*” OR “benefit transfer*” OR “willingness to pay” OR “travel cost*”	502	15
Groundwater (B)	Regulation of water quantity through porous media, Regulation of water quality through filtration, Groundwater resources for drinking, Groundwater used as a material	("artificial recharge" OR "groundwater abstraction" OR "groundwater recharge" OR "aquifer resource*" OR "groundwater quali*" OR "groundwater quanti*" OR "groundwater extraction" OR “groundwater resource*”)		OR “monetised” OR “willingness to accept” OR “monetarization” OR “monetisation” OR “valuation method*” OR “use value*” OR “non-use value*” OR ”option value*” OR ”existence value*” OR “altruistic	302	22
Underground space (C)	Space, Disposal and storage	(“underground space*” OR “subsurface space*” OR “UUS” OR “underground infrastructure*” OR “subsurface storage” OR “subsurface reservoir*” OR “underground storage*” OR “underground reservoir*” OR “underground cable*” OR “underground pipe*”)		value*” OR “bequest value*” OR “WTP” OR “WTA” OR “Non-market value*” OR ”production function” OR “choice experiment*” OR “damage cost avoided” OR “travel cost*” OR “mitigative expenditure*” OR “avertive expenditure*” OR “externalit*”)	44	9
Underground geomaterials and non-renewable energy resources (D)	Industrial minerals, Minerals for nutritional purposes, Construction materials, Ferrous ores, Base metals, Precious metals and Rare Earth Elements (REEs), Ornamental resources, Non-renewable energy resources	(“industrial mineral*” OR “construction aggregate*” OR “construction stone*” OR “construction aggregate*” OR “geo? material*” OR “mineral deposit*” OR “mineral resource*” OR “metallogenic resource*” OR “mineral extraction*” OR “mine*” OR “mining” OR “quarr*”)			1478	20

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Table B1 (*continued*)

Group	Geosystem services	Search string(s) used			
		Terms related to individual geosystem services	Economic terms related to non-market valuation	No. hits	Relevant hits
Renewable underground energy resources (E)	Regulation of temperature by the subsurface, Geothermal resources	("geothermal energy" OR "geo?energy" OR "geoenergy" OR "aquifer thermal energy storage" OR "borehole thermal energy storage")		44	2
Underground cultural heritage repository (F)	Iconic sites, Educational resource	("geoheritage" OR "geological heritage" OR "geotourism" OR "geoconservation" OR "geodiversity" OR "geopark" OR "geosite" OR "geomorphosite*" OR "geological archive*" OR "geoarchive*" OR "geoeducation" OR "Sites of Special Scientific Interest" OR "SSSI*")		43	3
Other (G)	Subsurface habitat	("abiotic servic*" OR "geosystem*" OR "geodiversi*" OR "subsurface habita*" OR "underground habita*" OR "stygo*" OR "troglo*" OR "subterranean habita*" OR "subterranean fauna" OR "underground fauna" OR "subsurface fauna")		38	0

Appendix C. Search return and relevant hits

Table C1
An overview of the search returns, number of relevant articles, valuation methods used and references. Please note that the same article may be referenced several times if said study assessed multiple services. A total of 71 relevant studies were found in the review. Abbreviations: BT = Benefit transfer, CE = Choice experiment, CM = Choice modelling, CV = Contingent valuation, DCA = Damage costs avoided, HP = Hedonic pricing, MP = Market price, PF = Production function, RC = Replacement costs and TC = Travel costs.

Group	Service	Valuation method(s)	Reference(s)
Stable and safe environment (A)	Regulation of erosion	DCA(2), CV(1), RC(1)	Dribek and Voltaire (2017); Hansen and Hellerstein (2007); Patault et al. (2021); Saengsupavanich (2019)
	Regulation of mass movements	DCA(1), HP(1), BT(1), PF(1)	Kim et al. (2017); Lee et al. (2021); Rangsiwanichpong et al. (2019); Vranken et al. (2013)
	Stable platform to build on and within	HP(2), MP(1), DCA(2)	Fleury (2007); Galve et al. (2012); Koster and Van Ommeren (2015); Sundell et al. (2019); Suter et al. (2019)
	Regulation of soil and bedrock chemistry	RC(1)	Hopkins et al. (2018)
Groundwater (B)	Regulation of water quality through filtration	CV(2), RC(1)	Brouwer et al. (2018); Damigos et al. (2017); Hérivaux and Grémont (2019)
	Regulation of water quantity through porous media	CV(1), HP(1), PF(1)	Acharya and Barbier (2000); Damigos et al. (2017); Tapsuwan et al. (2009)
	Groundwater for drinking	CV(4), HP(1), RC-PF-MP(1), RC(2), BT(1), CE(1)	Baniasadi et al. (2020); Hérivaux and Grémont (2019); Kerr et al. (2003); Legg et al. (2020); López-Morales and Mesa-Jurado (2017); Murray et al. (2006); Tentes and Damigos (2012); Tentes and Damigos (2015); Wei et al. (2007); White et al. (2001); Yoo and Perrings (2017)
	Groundwater used as a material	CV(7), HP(3), RC-PF-MP(1), RC(2), BT(1), CE(1), MP(3), PF-BT(1)	Baniasadi et al. (2020); Berbel et al. (2018); Bierkens et al. (2019); Chandrakanth and Arun (1997); El Chami et al. (2008, 2009); Hérivaux and Grémont (2019); Kerr et al. (2003); Knapp et al. (2018); Legg et al. (2020); López-Morales and Mesa-Jurado (2017); McCarl et al. (1999); Mukherjee and Schwabe (2014); Murray et al. (2006); Sampson et al. (2019); Tentes and Damigos (2012); Tentes and Damigos (2015); Wei et al. (2007); White et al. (2001); Yoo and Perrings (2017)
Underground space (C)	Space	RC(5), BT(1), CV(1), MP-BT (1)	Dong et al. (2021); Liu et al. (2021); Mavrikos and Kaliampakos (2007); Mavrikos and Kaliampakos (2021); Navrud et al. (2008); Qiao et al. (2017); Qiao et al. (2022a, 2022b)
	Disposal and storage	HP(1)	Jellicoe and Delgado (2015)
Underground geomaterials and non-renewable energy resources (D)	Industrial minerals	–	–
	Minerals for nutritional purposes	–	–
	Construction materials	MP - RC (1), CE (3), RC(1), HP (1)	Brown et al. (2011); Garrod and Willis (2000); Jaeger (2006); Lavee and Bahar (2017); Legg et al. (2020); Willis and Garrod (1999)
	Ores	BT(3), CE(1), CV(2), TC-CV(1)	Arendt et al. (2022); Asamoah et al. (2017); Crespo-Cebada et al. (2020); Damigos and Kaliampakos (2006); Huszar et al. (2001); Kosenius and Horne (2016); Mendonça and Tilton (2000)
	Ornamental resources	–	–
	Non-renewable energy resources	BT(4), HP(1), CM(1)	Cardoso (2015); Collins et al. (2012); De Valck et al. (2021); Mazzotta et al. (2015); Williamson et al. (2008); Windle and Rolfe (2014)

(continued on next page)

Table C1 (*continued*)

Group	Service	Valuation method(s)	Reference(s)
Renewable underground energy resources (E)	Regulation of temperature by the subsurface	–	–
	Geothermal resources	CV(1)	Horasanli and Alp (2010)
Underground cultural heritage repository (F)	Iconic sites	CV(3), TC(1), BT(1), PF-BT(1)	Berbel et al. (2018); Cheung (2016); Cook et al. (2018); Lienhoop and Messner (2009); Mishra et al. (2012); Pérez-Álvarez et al. (2016)
	Sacred and historical sites	–	–
	History and evolution of the Earth	–	–
	Educational resource	–	–
Other (G)	Subsurface habitat	RC(1)	(Qiao et al., 2022b)

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