THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Geosystem services to support decisions on subsurface use

EMRIK LUNDIN FRISK

Department of Architecture and Civil Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

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EMRIK LUNDIN FRISK

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Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
Illustration of geosystem services examples that can be relevant from subsurface perspective.

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EMRIK LUNDIN FRISK
Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
Chalmers University of Technology

ABSTRACT

Awareness of the subsurface is in general low and is not a daily concern for decision-makers. This often results in that decisions on access to subsurface resources instead are guided by a 'first come, first served principle'. This is precarious, as 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, the utilisation of other subsurface resources in the future, potentially impeding sustainable development.

Though not fully developed the concept of geosystem services (GS) has been put forward as a concept that can make these resources more visible and acknowledged in decision-making. However, a systematic literature review of scientific publications on geosystem services was carried out and the emerging picture is that the geosystem services concept is both one of novelty and one of discrepancy, with two prominent definitions: A) GS are abiotic services that are the direct result of the planet's geodiversity, independent of the interactions with biotic nature – there is no differentiation between suprasurface and subsurface features, and B) GS provide benefits specifically resulting from the subsurface. Of the identified geosystem services, 31 out of 39 are listed in the abiotic extension of CICES 5.1 (Common International Classification of Ecosystem Services), but some essential services are omitted.

To support well-informed decisions on the utilisation of subsurface resources, positive effects need to be weighed against negative effects on a society-wide level, not least regarding effects on the future supply of subsurface resources, or subsurface geosystem services. Cost-benefit analysis (CBA) is a method for providing a basis for such decisions by considering the positive and negative effects on human well-being (i.e., benefits and costs, respectively) on a societal level.

In this thesis, a generic CBA rule for assessing subsurface projects is applied to two theoretical cases to show conceptually how CBA can be applied for the prioritisation of competing uses of subsurface resources. The result from these two cases highlights that a systematic mapping of the effects that arise due to subsurface projects, using geosystems services as a point of departure, can make the consequences of such projects more visible and indicate who will be affected. The exemplification shows that a CBA can provide a basis for supporting decisions on prioritising competing subsurface uses, but that there is a need for complementary types of analyses to capture the wide range of benefits the subsurface provides. Finally, some supporting and possibly regulating geosystem services can be either intermediate or final services depending on analytical context, which is important to consider, not least in a CBA to avoid double counting.

Keywords: Geosystem services; Ecosystem services; Subsurface; Sustainability; Conflict of interests

LIST OF PUBLICATIONS

The following publications are appended to this thesis:

I. Lundin Frisk, E., Volchko, Y., Taromi Sandström, O., Söderqvist, T., Ericsson, L. O., Mossmark, F., Lindhe, A., Blom, G., Lång, L.-O., Carlsson, C., & Norrman, J. (2022). *The geosystem services concept – What is it and can it support subsurface planning?* Ecosystem Services, 58, 101483. https://doi.org/10.1016/j.ecoser.2022.101493

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B. Lundin Frisk, E., Merisalu J., Söderqvist, T., Volchko, Y., Ericsson, L. O., Rosén L. & Norrman, J. (2022). *Geosystem services and cost-benefit analysis to support a sustainable subsurface planning and utilization* [poster presentation]. Geological Society of America (GSA) Connect 2022.

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Finally, thank you for taking the time and effort to read this thesis. I hope that you, as a reader, will find it as interesting as I have found when writing it.

Kindly,
Emrik Lundin Frisk

Room SB-K435, Sven Hultins Gata 6
Chalmers University of Technology
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ABBREVIATIONS AND ACRONYMS

BT	Benefit Transfer method
CBA	Cost Benefit Analysis
CE	Choice Experiment method
CICES	Common International Classification of Ecosystem Services
CM	Choice Modelling method
CV	Contingent Valuation method
DCA	Damage Cost Avoided
ES	Ecosystem Services
GS	Geosystem Services
HP	Hedonic Pricing
MA	Millennium ecosystem Assessment
MCA	Multi-Criteria Analysis
MP	Market Price-based methods
NPV	Net Present Value
PF	Production Function-based approaches
PV	Present Value
RC	Replacement Cost methods
TC	Travel Cost method
TEEB	Economics of Ecosystems and Biodiversity
TEV	Total Economic Value
WTA	Willingness to Accept
WTP	Willingness to Pay

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1 INTRODUCTION

This chapter provides a brief background of the research, presents the overall research aim and the specific objectives of this thesis, as well as the scope of work, followed by clarifying the limitations.

1.1 Background

The subsurface has provided human societies with the most basic requirements since prehistoric times (e.g. de Mulder et al., 2012). The subsurface provides drinking water from natural springs or rivers, opportunities to extract energy, materials and metals, support for habitats and surface life, and hosts a repository of cultural heritage. This multi-functionality of the subsurface has only recently been recognised in the scientific literature (see e.g. the review by Volchko et al., 2020). Since industrial times, the subsurface has also been increasingly developed to provide physical space for infrastructure and to improve the surface environment, especially in and around cities, a trend that is predicted to increase with ongoing urbanisation (e.g. Evans et al., 2009). Yet, access to and use of the subsurface is widely governed by the 'first-come-first-served' principle (e.g. Dick et al., 2017). This is problematic since one use may hinder opportunities for using the subsurface for other purposes, thus limiting the benefits society might otherwise derive from the subsurface's multifunctionality. Therefore, there is an ambition to regulate the use of the subsurface by legislation in spatial planning processes (see e.g. de Mulder et al., 2012; Dick et al., 2017; Volchko et al., 2020).

However, the subsurface has traditionally been "out of sight and out of mind" unless either adverse subsurface conditions manifest themselves – such as the risk for landslides – or great opportunities are present – such as extraction of valuable geomaterials and mining (van der Meulen et al., 2016b). In more common geological settings and for less spectacular goods and services, the general awareness is often low and is not a daily concern for planners or a city's inhabitants (Dick et al., 2017; van der Meulen et al., 2016b). The dilemma with subsurface resources is that they are often hidden from plain sight and, as such, invisible to most non-experts (e.g. Dick et al., 2017; van der Meulen et al., 2016b). To overcome this issue, and to support a more holistic subsurface planning approach, the concept of geosystem services (GS) has been suggested as a way to highlight services from the subsurface (or which the subsurface provides), as a complement or parallel to how the concept of ecosystem services (ES) acknowledges the contribution of biotic part of nature to human well-being (Gray, 2011, 2018; van Ree & van Beukering, 2016; van Ree et al., 2017).

The concept of ecosystem services has brought attention to other complex and intangible benefits that humans derive the living (biotic) parts of nature and is widely accepted and embedded in global and national environmental policies. Although it is not yet fully integrated into spatial planning in practice, the concept has been used to raise awareness and to integrate various perspectives and disciplines into environmental management (i.e. functioning as a boundary object[1] e.g. Ainscough et al., 2019). Some abiotic services and goods are already included in the common ecosystem services frameworks (see e.g. the Common International Classification of Ecosystem Services, Haines-Young & Potschin-Young, 2018). However, ecosystem services are by definition the contributions that ecosystems make to human well-being. Services rendered by the non-living (abiotic) parts of ecosystems, including those derived from the subsurface, are often overlooked in ecosystem services studies (van der Meulen et al., 2016a; van Ree et al., 2017). Establishing the geosystem services concept as a parallel or a complement to ecosystem services could bridge this gap (see e.g. Gray, 2011, 2018; van Ree et al., 2017).

Highlighting the services and goods that are derived from the subsurface is a good point of departure, however, it is vital to also acknowledge that the use of these geosystem services is often associated with changes to the surrounding soil, sediment or bedrock properties. In turn, these changes can influence the supply of current (and future) use of other subsurface services and in turn jeopardise fair inter- and intragenerational distribution of said resources and sustainable development. Appropriate subsurface use has therefore been put forward as vital if we are to achieve resilient and sustainable communities (Admiraal & Cornaro, 2016; Admiraal, 2006). This implies that it is necessary to make sound strategic decisions on prioritisation and optimisation of competing subsurface uses and resolve potential conflicts of interest.

Planning of the subsurface to promote desirable social and environmental outcomes and efficient use of resources often necessitate resolving of potential conflicts of interest. By systematically summing up positive and negative effects due to an action (e.g., construction of a tunnel), decision-makers can get a basis for well-informed decisions on utilisation of subsurface resources. Cost-benefit analysis (CBA) is a widely used method for providing such a basis, taking 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. However, to able to compare benefits and costs, all relevant items are required to be converted to a common unit (typically a monetary unit) and aggregated. Thus, there is a need to quantify and to value geosystem services.

[1] Boundary objects are concepts that are elastic enough to be adapted to different contexts and discourses but contain enough immutable content to function as a channel of communication between these different positions (Star & Griesemer, 1989).

1.2 Aim and objectives

The overall aim of this thesis is:

> *to develop a better understanding of the concept of geosystem services and investigate the use of Cost-Benefit Analysis (CBA) as a decision support tool for prioritising conflicting subsurface uses of geosystem services.*

To reach the overall aim, the thesis has the following specific objectives:

i. *review and present definitions and conceptualisations of geosystem services,*

ii. *systematically map and compile non-market valuation studies in scientific literature that explicitly value changes in the supply of geosystem services in monetary units as result of abiotic changes in the subsurface,*

iii. *to demonstrate and discuss the use of CBA in two hypothetical subsurface projects.*

1.3 Scope of work

To achieve the aim and fulfil the specific objectives of this licentiate thesis, a multi-disciplinary approach was required. The disciplines that constitute the basis for this thesis included: geology, geomorphology, environmental science, environmental economics and spatial planning. To establish the context of this work, the thesis begins with a theoretical background that describes the frameworks, concepts and methods that underpin the thesis (Chapter 2). The methodology section (Chapter 3) describes the process to achieve the aim of the licentiate thesis and lists the main steps followed to fulfil the specific objectives: two systematic literature reviews and setting a basis for CBA. The result section (Chapter 4) presents the output of the research: (1) a description of geosystem services as a concept, (2) a review of how geosystem services have been valued in scientific literature, and (3) a (qualitative) demonstration of application of CBA for two hypothetical subsurface projects. In Chapter 5, broader implications, including how geosystem services can contribute to sustainable development of the subsurface, as well as limitations, are discussed. The main conclusions that can be drawn from this licentiate thesis are presented in Chapter 6, and Chapter 7 outlines ongoing work and suggests future work.

Fig. 1 illustrates the connection between the papers and the research objectives. Furthermore, the figure highlights the centre of attraction (focus) for each paper as well as periphery themes that constitute the foundation of these papers but is not addressed in detail. The work in this thesis revolve around two central themes, (1) definitions of geosystem services and (2) economic valuation of geosystem services.

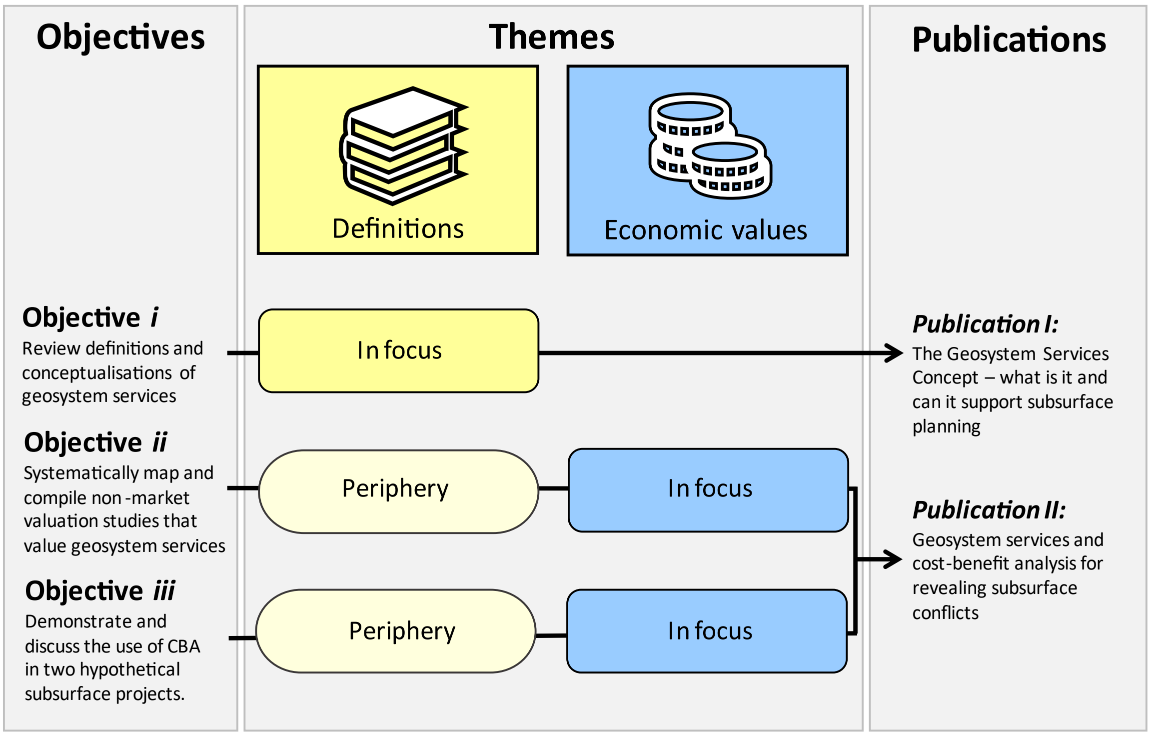

Figure 1: Schematic representation of how the appended publications relates to the research objectives and what themes they have in focus.

1.4 Limitations

The main limitations of this thesis are:

- The thesis relates to multiple scientific disciplines as the focus is on linking different fields, and as such it is limited in terms of in-depth explorations of each individual topic.
- Generalising (or globalising) examples of specific geosystem services, as done in this thesis and the two cases, inevitably lead to simplifications. The exemplification of geosystem services discussed are mainly derived from a Fennoscandian geological setting and are not necessarily applicable in other geological settings.
- Geosystem services as a concept is both one of novelty and one currently showing inconsistency (Publication I). Furthermore, the discourse surrounding the conceptualisation is rapidly developing. The literature search referred to in this thesis is limited to literature written in English and was carried out during 2021 – 2022. Therefore, some concurrent information of importance may have been missed in the writing of this thesis.
- This thesis primarily deals with preference-based valuation methods set in a neoclassical economics framework, which are commonly used in environmental economics, and easily translate to units that are readily understandable to most people, i.e., in monetary units such as dollars, euros and other currencies. While economic valuation is not per se a valuation in monetary terms, the term economic valuation and monetary valuation are used interchangeably throughout this thesis.
- The application of CBA is demonstrated in a Swedish setting placed in a European legislation context. Transferring examples, methods and results to other geological settings may be associated with transfer errors as both legislation and geological settings vary worldwide.

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2 THEORETICAL BACKGROUND

This chapter briefly presents some key concepts related to the research.

2.1 Geological type settings

Detailed geological investigations are expensive and time-consuming to perform and may not be possible to conduct due to time or financial constraints. As a substitute, experiences from previous works and available geological information (e.g., maps, investigations, articles, archives, etc.) are often used to come up with generalised descriptions of an area, known as a geological conceptualisation or a geological setting. These settings can in turn be used as a basis for detailed investigations or transferred to other sites that are similar but lack previous geological studies.

Geological (and geomorphological) settings can display a great range of heterogeneity. However, depending on formation and the basic building blocks that are available, some characteristics are shared between settings that have been formed in a similar manner. As such it is possible to formulate type settings that conceptualise a specific geological environment regarding its characteristic geological, geomorphological, hydrogeological and climate conditions. Such type setting summarises a description of all parameters of importance for a specific purpose and forms the basis for a conceptual model that can be used to make predictions regarding what geological structures can be found and what processes are active in a particular type of depositional environment.

A good example of the use of geological type settings in scientific literature is the study by Vacher and Wallis (1992) in which they used hydrogeological type settings to investigate and predict the formation of perched aquifers in two subtropical islands with similar geological settings depending on the average precipitation. In a similar manner, Holding and Allen (2015) used type settings more recently to characterise the susceptibility of small islands to be subjected to wave over-wash events that can result in severe consequences to the limited freshwater resources on these islands. By employing numerical modelling, they evaluated the freshwater lens response and recovery to over-wash events for a wide range of hydrogeological island type settings scattered worldwide. Hydrogeological type settings have also been employed in a wide range of studies in Sweden. For example, Eklund (2002) continued the work of Stejmar (1996) and used hydrogeological type settings developed for two provinces (Södermanland and Östergötland) to predict the potential for groundwater extraction based on the expected hydrogeological condition of these areas.

2.2 Ecosystem services

In short, ecosystem services are the many and varied contributions to human welfare provided by ecosystems to society (Millennium Ecosystem Assessment, 2005). These services include both indirect contributions (services) and direct contributions (goods) that add to human welfare:

- Indirect contributions are, for example, services provided by ecosystems, which indirectly contribute to human welfare, e.g. wetlands regulating water quality by filtering out harmful components from water.
- Direct contributions are, for example, goods that can be extracted from ecosystems and which can be used for a broad variety of applications, e.g. timber.

Over the last decades, three broadly accepted classification systems for ecosystem services have emerged that handle different aspects of ecosystem services classification and valuation. A short description of these systems follows below.

The Millennium Ecosystem Assessment (MA), was the first major international initiative to establish a scientific basis on how to sustainably, without undermining their long-term productivity, enhance the contributions of ecosystems to society. The work program was launched by United Nations Secretary-General Kofi Annan in June 2001 and was designed to link ecosystem services to human well-being and to investigate how ecosystem management can be adopted at local, national, or global scales and to investigate the current state of major ecosystems, trends in their production and flows, and threats to these systems (Millennium Ecosystem Assessment, 2005). The framework classifies four categories of ecosystem services, each underpinned by biodiversity, that contribute instrumentally and intrinsically to human welfare: (1) the regulating services describe the ways in which natural processes regulate the environment; (2) the supporting services describe the natural processes that support the environment; (3) the provisioning services describe the materials that are used by society, and (4) the cultural services describe the non-tangible elements of the environment that benefits society in a spiritual or cultural sense.

The Economics of Ecosystems and Biodiversity (TEEB) synthesis is an international initiative aiming to value the global economic benefits of ecosystems and biodiversity and the associated costs of biodiversity loss and ecosystem degradation to provide a bridge between multi-disciplinary science and international and national policies. The initiative was launched in 2007 after a Group of Eight + Five (G8+5) meeting in Potsdam, Germany and its main motive was to establish an objective global standard for natural capital accounting (TEEB, 2010b). The natural environment is viewed in TEEB (and elsewhere) as a form of capital asset, or natural capital, that includes forests, fossil fuels, minerals, water, and all other natural resources, regardless of whether these resources are traded on markets, are owned or not. Natural capital together with manufactured capital (e.g., infrastructure and technologies that contribute to the production process) and human capital (education, health and skills embodied in the workforce) form the basis for the assets that contribute to economic wealth and human welfare (see Barbier, 2019).

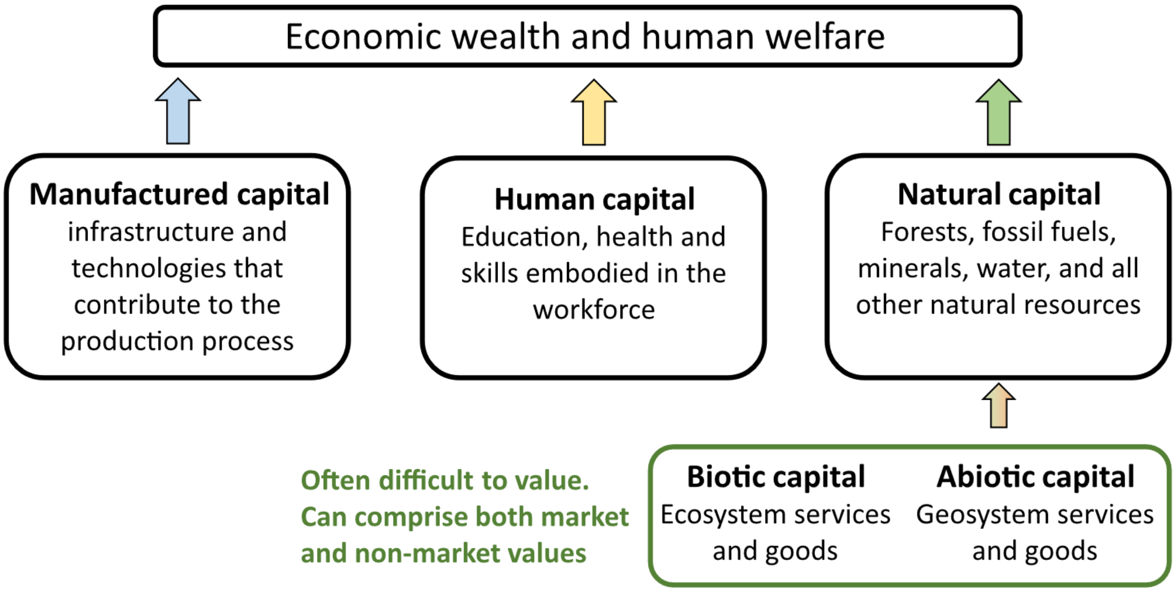

Figure 2: Illustration how manufactured, human and natural capital is connected to economic wealth and human welfare. Adapted from Barbier (2019), modified according to Fox et al. (2020).

The Common International Classification of Ecosystem Services (CICES), is widely used in categorising and describing ecosystem services and natural capital (Haines-Young & Potschin-Young, 2018). The CICES system was developed from the work on environmental accounting initiated by the European Environment Agency (EEA) with consultation from the international community. The main objective was to establish a common international classification for ecosystem services, as standardisation in the way ecosystem services are described was needed in order to develop ecosystem accounting methods and to make comparisons. The classification was initially introduced in 2009 (Haines-Young & Potschin, 2010, 2011) and was recurrently revised over the last decade. Although CICES acknowledges that the boundary between abiotic and biotic services is at best blurred, abiotic services were removed from the classification system in the classification from 2012 (CICES v4.3, Haines-Young & Potschin, 2012). Haines-Young and Potschin-Young (2018) have, however, reinstated abiotic services as an abiotic extension listing 35 abiotic services in the contemporary version (CICES v5.1, Haines-Young & Potschin-Young, 2018) of the CICES framework. The ecosystem services included in the classification are linked to the need of society on the one hand and the properties of the system on the other, with a series of intermediate stages between them as illustrated by the widely adopted cascade model, see Figure 3, introduced with CICES (Haines-Young & Potschin, 2011).

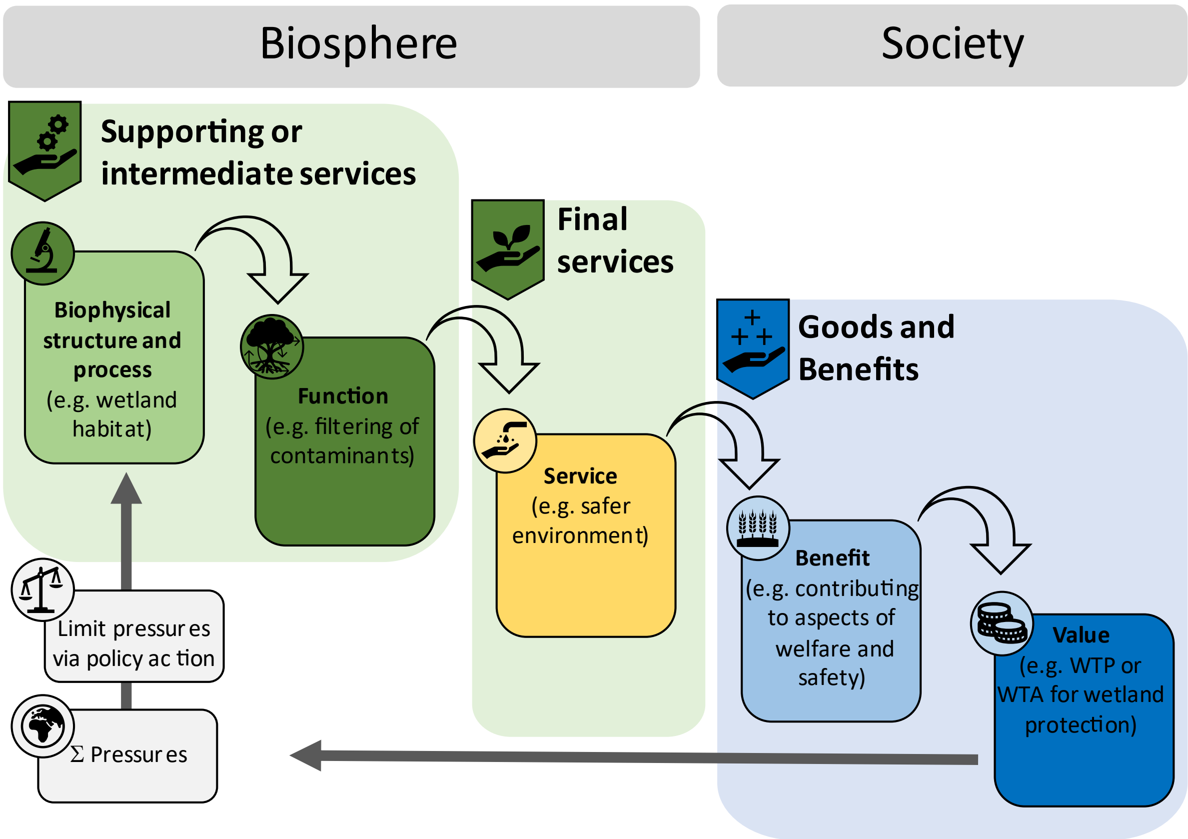

Figure 3: The cascade model, adapted from Haines-Young and Potschin (2010).The gray arrow represent pressure on ecosystems the develop as goods and benefits are used to enhance human welfare.

2.3 Economic value of services and goods derived from nature

Valuing services and goods derived from nature is often problematic, and as a result, they risk becoming overexploited (Pascual et al., 2010). For many of the provisioning services where there are well-developed markets, such as the extraction of minerals, there are reasonable estimates of their economic value (although one could argue whether this reflects the 'true' value, in which e.g., all externalities[2] are included). However, the economic value of cultural and regulating services, for which there is no existing market, is more difficult to estimate (Carpenter et al., 2006).

The neoclassical economics paradigm is a broad economic theory focusing on supply and demand as the forces that drive pricing and consumption of goods and services. As such, it is the utility[3] to consumers, rather than the cost of production, that is the most important factor in determining the value of a product or service. Environmental economic valuation methods are typically well rooted in the neoclassical paradigm, focusing on individual utility maximisation. Environmental services and goods are commonly classified according to their usage, broadly divided into use and non-use value categories, each with corresponding subcategories (Pagiola et al., 2004). Although

[2] An externality can be described as the positive or negative effects of a given economic activity that impose consequences for a third party that is not directly related to that activity (Johansson & Kriström, 2016, 2018).

[3] Utility in this context can be viewed as synonymous with welfare and well-being.

the terminology can vary, these categories broadly correspond to direct use values, indirect use values, option values and non-use values. In the following, these value categories are briefly elaborated and related to the different types of ES (regulating, supporting, provisioning, cultural) as used in the MA (2005).

- Direct use values are values that stem from directly using a resource, either for consumptive uses, such as the extraction of groundwater or non-consumptive uses such as enjoyment of recreational activities at a given site. These direct use values typically correspond to MA's definition of provisioning and cultural services (Pagiola et al., 2004).
- Indirect use values are those that provide benefits outside of themselves (e.g. regulating the physical environment, lowering the risk of flooding or mass movements). As these functions affect activities that have direct use, their value can be estimated through their impact on these activities. Indirect use values correspond broadly to MA's definition of regulating services (Pagiola et al., 2004).
- Option values are the values that arise from preserving services as an option to use in the future. As such these services are not to be used in the future, either by the present generation (option value) or by ensuring that future generations inherit this asset (bequest value). These option values, to the extent that they are not used at present but could be used in the future, together constitutes parts of provisioning, regulating and cultural services (Pagiola et al., 2004).
- Non-use values are values that are assigned to goods and services from just being aware of that the resources exist, even if that resource is not expected to be used. Non-use values are a kind of existence value that reflects the benefits people receive from knowing that a particular environmental resource exist, such as a national park (Pagiola et al., 2004). The non-use values can be further subdivided into bequest values, altruist values and existence values (Pascual et al., 2010).

By summing up the use (direct use value, indirect use-value, and option value) and non-use values (existence value), a total economic value (TEV) can be estimated (see Figure 4). This concept of a total economic value represents all components of (dis)utility derived, presently and in the future, from natural capital expressed in a monetary unit. The use of money as unit of measurement allows for comparison of the diverse benefits and costs associated with any given system (Pagiola et al., 2004; Pascual et al., 2010).

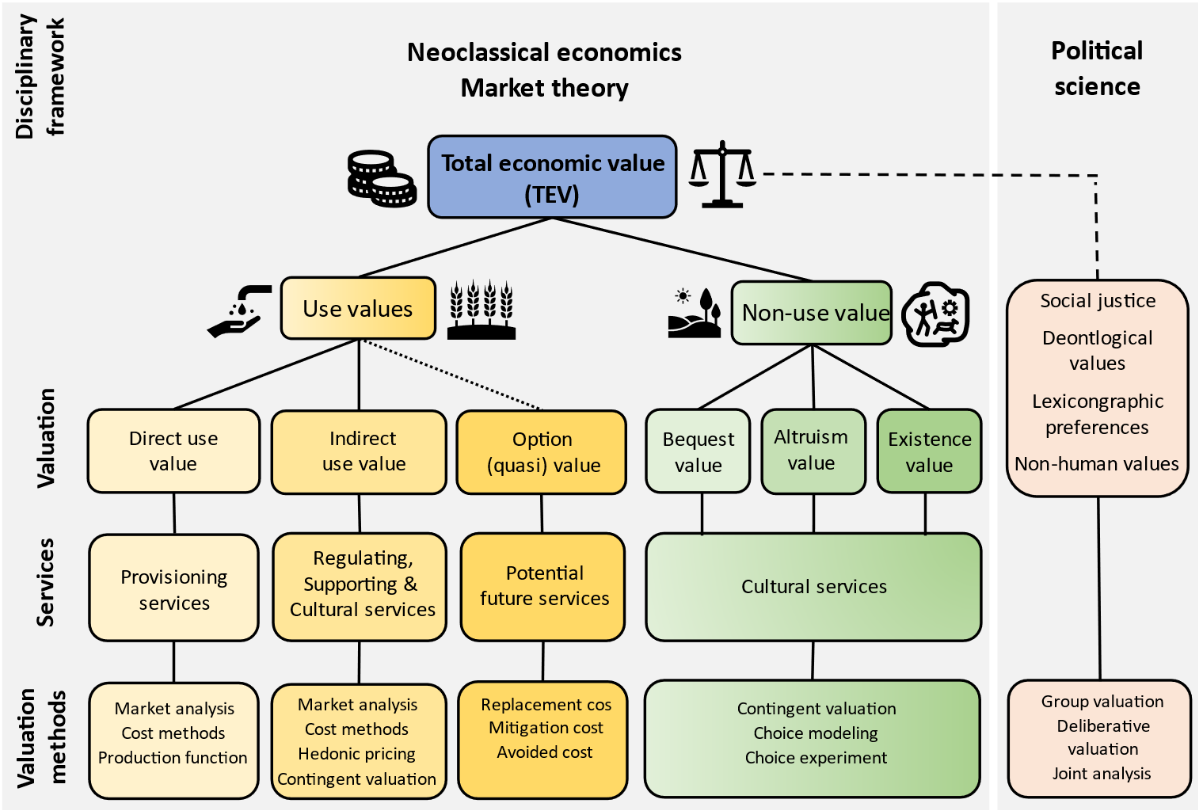

Figure 4: Illustration of total economic value (TEV) based on preference-based approaches. Adapted from TEEB (2010a), modified according to Adhikari and Nadella (2011).

The supporting services category delineated in MA (2005), which is composed of the services that underpin the production and delivery of the provisioning, regulating and cultural services are controversial in ecosystem services valuation frameworks as these services risk being double counted when they serve as inputs to other (multiple) services, i.e. they are intermediate services in the provision of final ecosystem services. As such, these services are rarely included in economic assessments.

2.4 Economic valuation methods

How do economists estimate the value of goods and/or services? If well-developed markets exist related to a specific service, monetary values are derived from market transactions relating directly to the said service which has a price (Pascual et al., 2010). This is common for many of the provisioning ecosystem services (Carpenter et al., 2006), such as timber extracted from a forest. In the absence of such a market, a value is either to be derived from parallel market transactions that are indirectly associated with the service or, if both direct and indirect market transactions are absent, a hypothetical market is created to be able to elicit monetary values (Pascual et al., 2010). This is a situation that is common for many of the cultural and regulating services (Carpenter et al., 2006), such as the ability of a wetland to regulate flood risks. Within the neoclassical economic paradigm, services that are created and consumed in the absence of a market are viewed as a type of positive externalities. In order to capture these non-marketed environmental goods and services, a large and still expanding collection of literature in environmental economics has been developed since the early 1960s. In essence, the monetary valuation of non-marketed services is done by either estimating the number of monetary units people are willing to pay (WTP) or are willing to accept (WTA) for preservation or enhancement of said service or can accept in compensation for its removal or deterioration. Common approaches available to estimate WTP or WTA are: (a) direct market valuation approaches, (b) revealed preference approaches and (c) stated preference approaches (Pascual et al., 2010).

The direct market valuation approaches comprise three main approaches: (I) market price-based approaches, (II) cost-based approaches, and (III) approaches based on production functions (Pascual et al., 2010). These approaches use data (prices, quantities and costs) that stem directly from actual markets and are as such often relatively easy to obtain and reflect true preferences or costs.

- Market price-based methods (MP) are used for services that produce commodities that are sold on markets. In well-functioning markets, the price of a commodity times the marginal product is a reliable indicator of the value of the service.
- Cost-based approaches such as the Replacement Costs (RC), Mitigative or Avertive Expenditure (MAE) and Damage Cost Avoided (DCA) are used in cases where replacement or damage avoidance expenditures can be estimated. These methods are an indirect way of estimating the value of a service, that relies on the assumption that the costs associated with the degradation of a service(s), must be worth at least what the cost to replace them is (de Groot et al., 2002).
- Production Function-based approaches (PF) are based on estimates of how much a given services (e.g. a regulating or supporting services) contributes to the delivery of another service or commodity that is traded on already existing well-functioning market (Pascual et al., 2010).

However, for many of nature´s goods and services, the markets are distorted or non-existent and are as such impossible to value through direct market valuation approaches (Pascual et al., 2010). Revealed preference approaches can be used when there are no explicit markets for a service as a more indirect means of assessing its value. These approaches rely on observing individual choices in existing markets on services that are related to the services that are the subject of valuation. Thus, the individuals "reveal" their preferences regarding the service that is valuated through these choices. However, revealed preference methods are both time-consuming and expensive to set up, as they require good quality data on each transaction, extensive data sets and statistical analysis. In addition, market imperfections and policy failures can distort the valuation study (Pascual et al., 2010). The two main methods related to revealed preference methods are the travel cost method and hedonic pricing.

- The Travel Cost method (TC) is mostly used to assess the value of recreational services. It is based on the assumption that the associated cost with using that recreational services (direct expenses and opportunity cost of time) represent the price of access to this recreational site. The number of visitors and how much they pay, i.e., the consumption behaviour of these visitors, reveals the willingness to pay for this service (Pascual et al., 2010).

- Hedonic Pricing (HP) is used to estimate values for an environmental attribute or service that directly influence marketed commodities. It is most commonly used to assess how different local environmental qualities (e.g. pollution or noise) and amenities (e.g. aesthetic views or proximity to recreational sites) influence property prices (Pascual et al., 2010).

Stated preference approaches are used to estimate both non-use values and/or use values for services for which there are no suitable surrogate markets from which a value can be derived. This is achieved by simulating a market and demand through surveys using hypothetical scenarios of different alternatives related to changes to the provision of a service. Stated preference approaches are often the only way of estimating non-use values, however, one of the main problems with these approaches is the divergence between the WTP and WTA seen in serval studies possibly due to the wide range of potential sources of biases in responses (Pagiola et al., 2004), such as hypothetical bias causing individuals to overstate their economic valuation of said service or good (e.g. Murphy et al., 2005). Another important problem is the controversy on whether non-use values, such as bequest or altruist values, can be stated in monetary terms (Pascual et al., 2010). The three main types of stated preference techniques are:

- Contingent Valuation method (CV) is a direct survey approach that use questionnaires to ask people how much they are WTP or WTA to enhance or preserve a service or, alternatively, how much they are willing to accept in compensation for its degradation or removal (Pascual et al., 2010).
- Choice Modelling (CM) is a direct survey approach that the use questionnaires to create a hypothetical market in which goods and services can be traded. The respondents are asked to express their maximum willingness to pay (WTP) or minimum willingness to accept (WTA) for a hypothetical change in the provision of a service (Pascual et al., 2010).
- Choice Experiment (CE) is an indirect survey approach that use questionnaires in which the respondents are asked to pick between different groups of environmental goods or services which are described in terms of their attributes. If a price is included as an attribute, it can be used to derive a monetary value of the other attributes (Pascual et al., 2010).

In some situations, if a budget for primary studies is lacking, benefit transfer methods can be used to estimate economic values for services. Benefit transfer methods are built on the assumption that available information from studies at a specific location can be used to estimate the monetary value of services at another location with a similar context. However, it should be noted that contexts that at a glance appear to be similar are not necessarily so, which could result in significant transfer errors (Pascual et al., 2010).

2.5 Cost-Benefit Analysis (CBA)

Cost-benefit analysis (CBA) is a method for providing bases for decisions regarding conflicts of interest, with widespread application with respect to both countries and policy areas (Boardman et al., 2018). CBA takes into consideration positive (benefits) and negative (costs) impacts on human welfare on a societal level, including present and future generations. The idea behind CBA is deceptively simple: it is a technique for establishing whether the benefits of a particular action are greater than the costs and thus, if carried out, would benefit society. An action in this context can broadly be divided into two types (Hanley & Barbier, 2009):

- Policy-oriented, deciding on whether to introduce or reform a particular government policy, e.g., introduce a new environmental tax (see e.g. the overview of CBA in British environmental policy in Pearce, 1998).
- Project-oriented, deciding on whether to go ahead with a particular investment, e.g. building a hydroelectric dam (see e.g. the brief historical background to CBA in Mishan & Quah, 2020).

To assess whether to carry out a given action, the benefits of said action (e.g. a project or a policy) are aggregated and compared with the aggregated costs. If the benefits are greater than the costs, society is better off if the project or policy goes ahead, and vice versa. This requires that all relevant benefits and costs are measured in the same units as otherwise they cannot be aggregated easily. The measurable unit used in CBA is monetary units, such as dollars, euros, or any other currency (Boardman et al., 2018; Johansson & Kriström, 2016, 2018; Mishan & Quah, 2020), and the general principle is to value negative and positive impacts of a project, i.e. costs and benefits, relative to the baseline reference (Hanley & Barbier, 2009). For some goods and services, this information is contained in market prices. However, for goods and services where the market 'fails' and externalities arise, for example when actions impose a cost to others (e.g., excessive groundwater withdrawal for irrigation causes drinking wells to dry up) or for goods that no market exists for (e.g., aesthetically pleasing landscapes) market prices are no longer a good guide to social costs and benefits (Mishan & Quah, 2020).

When all relevant costs and benefits, that can be expressed in monetary terms, have been accounted for, they are converted into a present value (PV) to account for that most cost and benefits are valued differently depending on when in time they are received. This temporal component is in CBA handled by a discount rate that is applied to benefits and costs that are expected to occur in the future in order to convert them into a PV. The discount rate allows for comparison of costs and benefits that occur at different times, the further away in time a cost or benefit occurs, the lower the discount factor (Hanley & Barbier, 2009).

As stated, the main purpose of CBA is to support the decision on what projects and policies are desirable in terms of their use of resources from societal perspective. Thus, if the sum of discounted gains (written as ($\Sigma B_t(1+r)^{-t}$) of a project or a policy exceeds the sum of discounted losses (written as: ($\Sigma C_t(1+r)^{-t}$), it can be regarded as a favourable use of resources for society as a whole (i.e. NPV > 0), given the setup and data used in the CBA. The summarisation of discounted gains and discounted losses, is known as a Net Present Value (NPV) test, where the value of an action can be described as:

$$NPV = \sum B_t\,(1+r)^{-t} - \sum C_t(1+r)^{-t}$$

in which the summations (Σ) run from the first year of the project or policy, $t = 0$, to the last year, t = T with the discount rate of r (Hanley & Barbier, 2009). There are other alternatives to the use of NPV. Two commonly used alternatives are the Internal Rate of Return (IRR) and Benefit-Cost Ratio. However, a description of advantages and disadvantages of employing these are out of the scope for this thesis and are not thoroughly discussed here. For a more detailed view, see e.g. Hanley and Barbier (2009) or Mishan and Quah (2020).

Cost-benefit analysis is useful as it addresses what is a fundamental economic problem: how to allocate scarce resources in face of (unlimited) demands. A cost-benefit analysis is a systematic and transparent way of describing the economic impacts of a project or policy over time, that allows, by means of a distributional analysis, to identify both the stakeholders that enjoy the gains and those that suffer the losses due to an action.

3 METHOD

This chapter presents the methodology applied to realise the research aims and objectives.

The methodology to achieve the overall aim and specific objectives of the thesis entailed (1) synthesising a theoretical foundation of geosystem services and their valuation through two literature reviews, (2) outlining a CBA rule for assessing subsurface projects, and (3) demonstrating and discuss the application of CBA in two hypothetical subsurface projects. The systematic literature reviews were carried out for investigating i) the concept of geosystem services and ii) the existence of monetary valuation studies of non-market goods and services derived from the subsurface. The two hypothetical cases were developed for demonstrating the application of CBA with a focus on subsurface geosystem services. The following sections provide some more details as to how these parts were carried out, and Paper I and Paper II describes the methodology of each study even more detailed.

3.1 Systematic literature reviews

The systematic literature reviews were carried out 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 as not all parts of the PRISMA statement were relevant (e.g., sensitivity analyses and certainty assessments) and to accommodate that a single researcher instead of two independent researchers carried out the study selection and data extraction. For details on e.g., search strings and the number of returned hits, see appended publications.

3.1.1 Geosystem services as a concept

The aim of the systematic review on geosystem services as a concept was to identify articles in which a definition of geosystem services was given, or could be inferred from, or in which examples of geosystem services were provided. Articles which met one (or both) of these two criteria were considered eligible. Emphasis was placed on journal articles that were geared towards geosystem services or abiotic services, published in primarily geoscientific, geoconservation or ecosystem services literature. Only peer-reviewed texts in English were included. The three key activities were: 1) identify and collect relevant research (mapping of research field), 2) critically appraise the research articles in a systematic manner, and 3) combine the findings into a coherent statement (a synthesis of geosystem services).

The following search strings were applied to the Scopus database: “geosystem”, “geodiversity”, and “abiotic services”. The broader search terms “geodiversity” and “abiotic services” were used to capture geosystem services and associated benefits that are discussed outside of the geosystem services’ terminology. Peer-reviewed articles or conference papers that met the criteria outlined in Table 1 were considered eligible for this study.

Table 1: *Inclusion and exclusion criteria used during the literature review of conceptualisations of geosystem services.*

Inclusion criteria during screening	Exclusion criteria during eligibility
I. Peer-reviewed original research article, meta study, or systematic review.	i. Do not address abiotic (ecosystem) services or have an inherent consideration of geosystems services as a concept.
II. A definition of geosystem services was given or could be inferred from.	ii. No full-text available.
III. One or more examples of geosystem services were provided.	
IV. Written in English.	
V. Abstract available.	

3.1.2 Valuation of geosystem services

The systematic review of valuation studies aimed to collect peer-reviewed articles and conference papers that have used mainstream environmental economics to, in monetary terms, value changes in the provision of geosystem services and ecosystem services caused by changes of the abiotic structures and processes of the subsurface (e.g., sand extraction from a delta deposit). The review is made broader than just focusing on geosystem services that are relevant for the hypothetical cases in order to investigate the access in general to economic valuation studies of geosystem services as (Gray, 2018; van Ree et al., 2017) have suggested that abiotic services often are omitted in environmental studies. Studies valuing effects on both geosystem services and ecosystem services due to an abiotic change was included in the review as it is difficult (and perhaps unjustified) in some cases to separate the services form each other.

Table 2: Inclusion and exclusion criteria used during the literature review for valuation of geosystem services.

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

For example, upstream sand mining can both change the river geomorphology (geological and geomorphological structures and processes) and effect the ecosystems that depend on the river's biophysical and biochemical structures and processes, thus causing loss of both geosystem services and ecosystem services. Peer-reviewed articles that met the criteria outlined in Table 2 were considered eligible for this study. Only texts written in English were included.

An illustration of the studies targeted for the review is shown in Figure 5 based on the Geo-Eco services cascade model developed by (Fox et al., 2020). To avoid multiple duplicates for each search, the geosystem services were sorted into larger groups of presumably overlapping services (e.g., Groundwater resources for drinking and Groundwater used as a material). Seven groups were created in total: A) Stable and safe environment, B) Groundwater, C) Underground space, D) Underground materials resources, E) 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 mainstream economic valuation terms and methods. The targeted keywords match terms and expressions commonly used for these resources, however, broader search terms such as "erosion" or "groundwater" were avoided as these returned an unmanageable number of hits. After screening the titles, abstracts and keywords of the remaining records in each group, items that contained the search terms, but which were unrelated to geosystem/ecosystem services and 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).

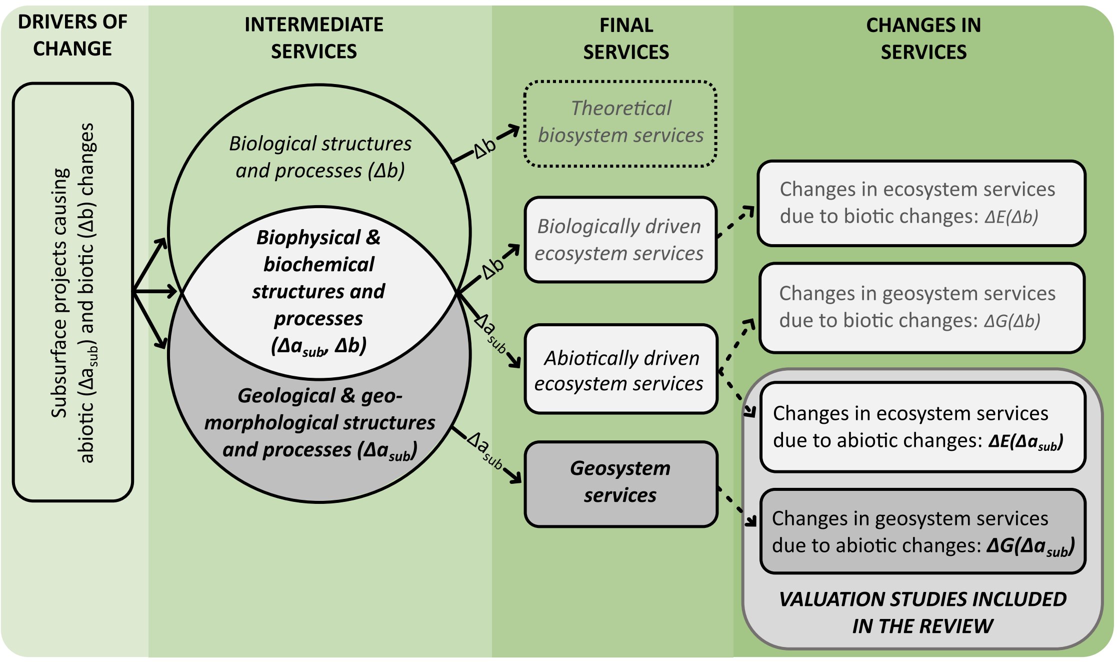

Figure 5: Illustration of studies targeted for the review. The conceptualisation of services is developed based on the Geo-Eco services cascade model (Fox et al., 2020).

3.2 Identification of geosystem services included in common environmental frameworks

After the initial step of identifying relevant publications, examples of geosystem services and their categorisation in the aforementioned literature were identified. Examples of associated benefits of geosystem services were either identified from this literature and for the services that lacked examples, benefits were suggested by the authors. In order to explore which services are already included in common ecosystems services framework, the list of geosystems services was then sorted according to whether these services were included or missing from the abiotic extension of the well-established CICES V5.1 framework (Haines-Young & Potschin-Young, 2018).

Not all services listed in aforementioned literature relates to the subsurface, thus as a final step, the geosystem services that can be relevant to include in a subsurface planning context were identified based on the examples provided in these texts. For a more comprehensive description of the geosystem services that are relevant from a subsurface perspective and the selection criteria used, see publication I.

3.3 A CBA rule for assessing subsurface projects

The idea of the CBA rule is rather straightforward: to assess whether the benefits associated with a subsurface project are greater than the costs in comparison to a reference alternative (often "do nothing"). The main purpose is to help select projects (and/or policies) that are efficient in terms of their use of resources. This is done via a net present value (NPV) test. A positive NPV implies that the project is beneficial from a societal perspective, a negative value is indicative of the opposite.

Following Johansson and Kriström (2018), goods and services having a market price can be evaluated by a vector with present values of producer prices of market goods (p), a vector with the changes in supplied quantities of market goods and services caused by the project (Δx^s) and present value change in total costs due to the project or policy (ΔC). The project's impact on non-market goods and services (S), i.e. those that lack market prices, can be economically valued through the associated WTP or WTA to have continued (or enhanced) supply of said service or acceptable compensation for their degradation (Freeman et al., 2014). The non-market goods and services can be evaluated by vector with the changes in available quantities of non-market goods and services caused by the project (ΔS) combined with a vector with present values of aggregate WTP or WTA per unit for these changes (w). Lump-sum taxation is assumed for simplicity and Δm^L denotes the change in present value lump-sum payment (positive or negative). Thus, the NPV of a subsurface project's can be written as:

$$\mathrm{NPV} = p\Delta x^s - \Delta C + \Delta m^L + w\Delta S$$

When assessing subsurface projects, the vector S includes both non-market geosystem services (a vector G) and non-market ecosystem services (a vector E). A project might influence G and/or E through its impact on abiotic (a) and biotic (b) properties.

However, in the two theoretical cases that the CBA is applied to in this thesis, only the impact of a project on subsurface abiotic properties (a_{sub}) and consequences to the available supply geosystem services and ecosystem services is accounted for. That is, we have exemplified $w\Delta G(\Delta a_{sub})$ and, to some extent, $w\Delta E(\Delta a_{sub})$ as part of $w\Delta S$, where ΔG and ΔE are caused directly by Δa_{sub} in these cases.

3.4 Application in two theoretical cases

This section presents the methodology used to apply CBA to evaluate two hypothetical projects set in two separate but common Fennoscandian geological settings in which new usages of the subsurface will give rise to a conflict of interests. In this thesis, a geological setting is defined as follows:

> *A geological setting is the geological, geomorphological, hydrological and climatic conditions of the area including the active processes (thermal, hydraulic, mechanical, chemical and biological) that take place within this environment.*

The focus in this thesis is to evaluate the effects on geosystem services and ecosystems services due to changes to the geological substrate and is carried out in four steps. Descriptions of these four steps are outlined below.

Step I refers to contextualising and setting the boundary conditions for the analysis. In this case, defining the scope as a CBA and establishing a conceptual understanding of the natural subsurface conditions in the two hypothetical cases using the idea of geological settings (Figure 6). For detailed descriptions of the two geological settings see methodology section of publication II.

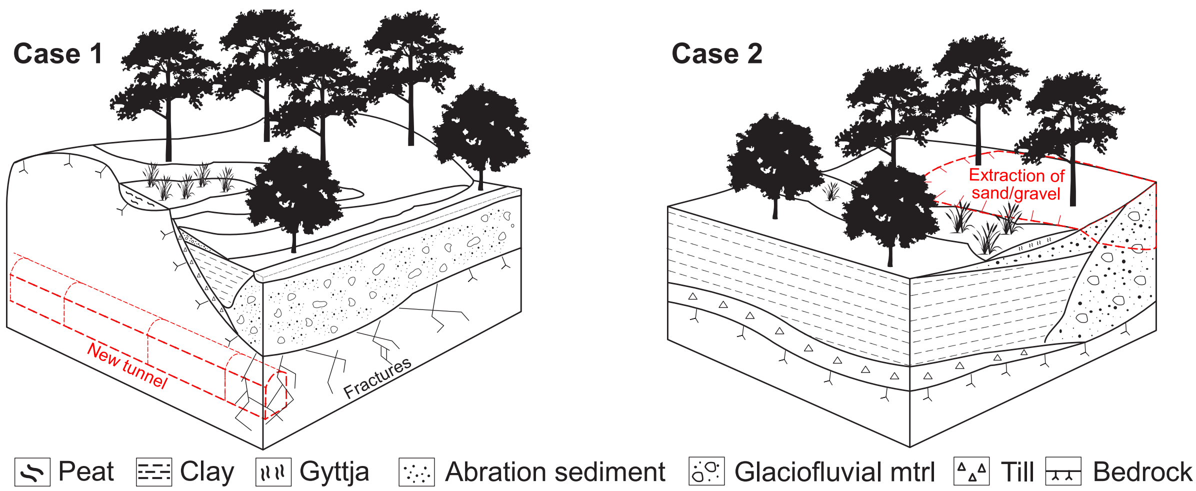

Figure 6: Illustration of the two geological settings for case 1 and case 2

Step II consists of mapping the effects that the two hypothetical subsurface projects will cause due to that the projects are seen as drivers of, primarily abiotic, change. In publication I, a list of geosystem services that are relevant for subsurface planning was suggested. This suggested list is used as a basis for the mapping of effects. For each of the geosystem services listed, the effects of the hypothetical projects are qualitatively (and partly hypothetically) described from a process-oriented perspective with a focus on interactions between thermal, hydraulic, mechanical, chemical, and partly biological processes. The resulting change (impacts) are described as either negative, positive, positive or negative, or no effects.

Step III is to identify and categorise cost and benefits items, to be included in the CBA. The mapping carried out in Step II is used as support to identify these posts, but other items that are relevant (such as reducing travel time) are also added to the cases. All cost and benefit items are sorted into market goods and non-market goods, and the non-market goods are divided into three groups: the non-market goods related to i) supply of geosystem services, ii) supply of ecosystem services, and iii) all other types of non-market goods included in the vector S (Section 2.5) caused by the subsurface projects.

Step IV is to quantify and monetise the costs and benefits items that are relevant. In a full CBA, quantification and monetisation are crucial steps, however, in the analysis of these hypothetical cases these steps have not been carried out to the full extent. Monetisation often requires primary studies that are resource-demanding, so a first step is often to investigate the possibility to transfer this type of data from other valuation studies that have been carried out in a similar geological setting. Therefore, a systematic review was carried out to identify to which extent such studies already exist (see Section 3.1.2). In order to investigate the access in general to monetary valuation studies of geosystem services, the review was made broader than just focusing on geosystem services that are relevant for the hypothetical cases suggested here (section 3.1.2).

4 RESULT

This chapter summarises the main results, starting with a presentation of geosystem services conceptually and with examples of services, followed with how geosystem services can be valued and two examples on how geosystem services can be included in a CBA.

4.1 What are geosystem services?

The geosystem services concept is one of novelty, with articles on the topic all emerging within the last two decades, and one of discrepancy, as authors have emphasised different aspects and have envisaged different approaches to connecting abiotic services to the ecosystem services framework. In the first study on geosystem services (Paper I), two prominent definitions of geosystem services were found in scientific literature: geosystem services as underpinned by geodiversity (definition A), and geosystem services as related to services from the subsurface (definition B).

A. Fox et al. (2020), referring to Gray (2011), defined geosystem services as "all services associated with geodiversity independent of interactions with biotic nature" (Fox et al., 2020, p. 152). In this definition, geodiversity underpins and forms the basis for the flow of services stemming from both the biotic (ecosystems) and abiotic (geosystem) features of nature. Early definitions of geodiversity were synthesised and later redefined by Gray (2013, p. 12) as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems, and contributions to landscapes".

B. van Ree and van Beukering (2016) and van Ree et al. (2017) defined geosystem services as "the goods and services that contribute to human welfare specifically resulting from the subsurface" (van Ree & van Beukering, 2016, p. 34). The authors formulated a distinction between the stocks (e.g. mineral resources, stability) and the flows of services (associated with geological, energy and material cycles) stemming from these stocks. The geosystem services were differentiated from ecosystem services by van Ree and van Beukering (2016) as the geosystem services originate from the deep-seated stocks, rather than from the critical zone where most of the biotic activity takes place. The boundary is delineated by the strong decline in biological activity, located in the pedosphere, which forms a transition zone between the two types of services (van Ree et al., 2017).

The difference between the two definitions outlined above of is not only (geo-)spatial but also, in part, reflects a different approach to the interactions between abiotic and biotic components. Gray (2011, 2018) referred to geosystem services as the wide range of abiotic services that stem from the planet's geodiversity, independent of the interactions with biotic nature – in this sense, geosystem services constitute only the contributions from the abiotic parts of nature and there is no differentiation of (supra)surface and subsurface features. Authors van Ree and van Beukering (2016), on the other hand, define geosystem services as the natural capital and services related to the subsurface. In this definition both the biotic and abiotic are included. Although, the subsurface is generally associated with low biological activity, due to the lack of sunlight and often anaerobic conditions, it still hosts microorganisms (e.g. stygofauna and troglofauna) that are beneficial to human society and are thus included in van Rees's definition of geosystem services (van Ree et al., 2017).

Table 3 summarises all identified examples of geosystem services from the reviewed literature, categorised into "regulating", "supporting", "provisioning" and "cultural" services. Gray (2011) additionally included "knowledge" services separately, but these are formally recognised as part of cultural services in the Millennium Ecosystem Assessment (MA, 2005). The table show how the two views (definitions A and B) of what the geosystem services concept constitutes have resulted in different examples being used to typify geosystem services. Some of these examples are shared by both definitions whilst others differ.

The geosystem services that were identified in the reviewed literature have been sorted according to whether they were included in, or missing from, the abiotic extension of CICES v5.1. Table 3 shows that thirty-one out of thirty-nine geosystem services listed in the reviewed literature are already included in the abiotic extension of CICES. However, the study by van Ree et al. (2017) imply that the alignment of the abiotic services included under CICES v5.1 is perhaps more limited than Table 3 would suggest, as for every publication on subsurface services 140 articles on ecosystem services have been published during the last two decades. The services that are missing from CICES are foremost the supporting services. While the supporting services category is included in both definitions of geosystem services, they are controversial in common ecosystem services frameworks such as CICES and environmental accounting as these services may pose a risk of double counting when they serve as inputs to other ecosystem services. These intermediate or supporting services are in other words an intermediate step in the provision of the final ecosystem services (Jax, 2016; Potschin & Haines-Young, 2016; Rives et al., 2016).

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Table 3: List of geosystem services found in the reviewed literature. Interpretations are made of the geosystem services listed in literature to provide examples of use, associated benefits, and the spatial origin of each geosystem service. Services deemed as relevant from a subsurface perspective in publication I are marked with bold.

Category	Geosystem Service: Included in the abiotic extension of CICES V5.1? Yes (CICES code)	No	Def	Interpretation: Example of uses	Associated benefit(s)	Spatial origin
Regulating services	Regulation of surface water quality (lakes, reservoirs etc.) by dilution (5.1.1.1)		A	Use of freshwater/marine systems as a pollution sink	Disposal of waste, reduction in costs for handling waste	Surface - subsurface
	Regulation of oceanic chemistry (5.1.1.3)		A	Use of e.g. calcium carbonate dissolved in terrestrial flowing water to buffer the oceanic pH	Reduction in loss of biotopes and biodiversity	Surface - subsurface
	Regulation of erosion (5.2.1.1)		A	Use of e.g. passive erosion protection systems	Reduction in damage costs	Surface - subsurface
	Regulation of mass movements (5.2.1.1)		A	Regulation of groundwater levels to prevent landslides	Reduction in damage costs and providing a safer environment	Surface - subsurface
	Regulation of baseline and extreme events, flow of water (5.2.1.1 & 5.2.1.2)		A	Use of e.g. natural levees to protect from flooding	Reduction in damage costs and providing a safer environment	Surface - subsurface
	Regulation of water quantity through porous media (5.2.1.2)		A, B	Use of porous media such as sand and gravel to infiltrate, store and transport water	Reduction of flooding and associated damage costs in cities by allowing storm water to infiltrate	Subsurface
	Regulation of water quality through filtration (5.1.1.3)		A, B	Use of porous media to filtrate pollution, bacteria and other nuisances from groundwater	Reduction in treatment costs. Increased environmental quality	Subsurface
	Regulation of limnological chemistry (5.1.1.1)		A	Use of e.g. calcium carbonate dissolved in (flowing) water to buffer pH in limnological systems	Reduction in loss of biotopes and biodiversity	Surface - subsurface
		Regulation of the hydrological cycle	A	Regulation by e.g. topographical elevation to channel or block the passage of rain-producing weather systems (rain shadow)	Providing a stable (local) climate	Suprasurface - surface - subsurface
	Regulation of atmospheric chemistry (5.1.1.2)		A	Use of e.g. abiotic carbon sequestration (CSS) to regulate atmospheric greenhouse gases	Reduction in predicted damage cost of climate change impacts	Suprasurface - surface - subsurface
		Regulation by the thermal buffer capacity of the subsurface	B	Use of the subsurface as a heat exchanger (e.g. for shallow geothermal energy systems)	Reduced heating and/or cooling costs	Subsurface
	Regulation of soil and bedrock chemistry (5.2.2.1)		A, B	Use of the subsurface and associated (bio)geochemical processes to buffer pH in soils and bedrock	Reduction in loss of biotopes and biodiversity	Surface - subsurface

Category	Geosystem Service: Included in the abiotic extension of CICES V5.1? Yes (CICES code)	No	Definition	Interpretation: Example of uses	Associated benefit(s)	Spatial origin
Supporting services		Retention of water in soils	A	Use of soil cavities to retain water in soil, which in turn is used by plants and other organisms	Contributing to plant productivity and soil health	Surface - subsurface
		Soil development	A	Use of weathering products to add nutrients to the soil	Contributing to soil renovation, increasing plant productivity	Subsurface
		Retention of nutrients in soils	A	Use of the soil ability to retain nutrients	Contributing to soil fertility and soil health	Subsurface
		Habitat provision (marshes, caves, beaches etc.)[4]	A	Use of the natural environment by an organism adapted to surviving in that environment	Contributing to a diverse landscape and to biodiversity	Surface - subsurface
		Stable platform to build on and within	A, B	Use of the (sub) surface to build on	Contributing to a platform to build on and within	Subsurface
		Space (for construction and infrastructure)	A, B	Use of the (sub) surface for space	Relieves the increasingly congested surface. Can provide protection for sensitive activities.	Subsurface
		Disposal and storage	A, B	Use of the subsurface to bury and store waste or materials underground	Natural formations can provide good storage space without expensive construction for e.g. water and carbon dioxide. Waste has commonly been buried, for example, to prevent e.g. spreading of dust, smell, radiation etc.	Subsurface

[4] Habitat provision as a service is not included in the abiotic extension of CICES. However, it is included in CICES as a biotic service under Regulation and Maintenance (CICES code 2.2.2.3).

Category	Geosystem Service Included in the abiotic extension of CICES V5.1? Yes (CICES code)	No	Definition	Interpretation Example of uses	Associated benefit(s)	Spatial origin
Provisioning services	Surface water resources for drinking (4.2.1.1)		A	Use in public water supply systems	Access to clean drinking water	Surface
	Groundwater resources for drinking (4.2.2.2)		A, B	Use in public water supply systems, mineral water	Access to clean drinking water that requires little treatment	Subsurface
	Surface water energy resources (4.2.2.2 & 5.2.1.3)		A	Use of freshwater as an energy source	Renewable energy source	Surface
	Surface water used as a material (non-drinking purposes) (4.2.1.2)		A	Use of surface water for e.g. cooling purposes or for irrigation	Reduces energy costs. Reduced material costs	Surface
	Groundwater used as a material (non-drinking purposes) (4.2.2.2)		A, B	Use of groundwater for e.g. irrigation or as a component in industrial processes. Recharge of lakes, rivers, and wetlands.	Reduces energy costs. Reduced material costs	Subsurface
	Industrial minerals (4.3.1.2)		A, B	Use of minerals, such as graphite by industry, based on their physical and/or chemical properties	Access to these minerals	Subsurface
	Minerals for nutritional purposes (4.3.1.1)		A, B	Use of minerals, such as salt, for nutrition	Access to these minerals	Subsurface
	Non-renewable energy resources (4.3.1.3)		A, B	Use of oil, natural gas, uranium resources etc. to provide energy	Energy sources	Subsurface
	Geothermal resources (4.3.2.5)		A, B	Use of groundwater to heat or cool buildings	Reduced heating and/or cooling costs. Renewable energy source	Subsurface
	Construction materials (e.g. rock aggregates, sand and gravel) (4.3.1.2)		A, B	Use of materials, minerals and rock for construction works	Access to these construction materials	Subsurface
	Ferrous ores, Base metals, Precious metals and Rare Earth Elements (REEs) (4.3.1.2)		A, B	Use of metallic minerals, such as copper and lithium, for industrial purposes	Access to these minerals	Subsurface
	Ornamental resources (4.3.1.2)		A, B	Use of mineral and/or rocks, such as metals, gemstones and marble, for ornamental purposes	Access to these ornamental resources	Subsurface

Category	Geosystem Service Included in the abiotic extension of CICES V5.1? Yes (CICES code)	No	Definition	Interpretation Example of uses	Associated benefit(s)	Spatial origin
Cultural services *Knowledge services, formally part of Cultural services in the MA classification.*	**Iconic sites (e.g. for cave exploration) (6.1.1.1)**		A	Use of caves for exploration	Tourism	Surface - subsurface
	Recreational sites (e.g. rock-climbing sites and trail-running tracks) (6.1.2.1)		A	Use of rock faces for climbing, tracks to run on etc.	Recreation and tourism	Surface - subsurface
	Aesthetic landscapes (6.2.2.1)		A	Viewpoints for iconic mountain peaks, undulating landscapes etc.	Tourism and recreation	Surface - subsurface
	Sacred and historical sites (6.2.1.1)		A, B	Use of sacred and historical sites to understand our history	Tourism and scientific endeavours	Surface - subsurface
	History and evolution of the Earth (6.1.2.1)		A	Use of distinctive geological, geomorphological or mineralogical sites to understand the history of Earth	Tourism and scientific endeavours	Surface - subsurface
	History and evolution of life (6.1.2.1)		A	Use of fossils to understand the history of life on Earth	Tourism and scientific endeavours	Surface - subsurface
	Paleoclimates and paleoenvironments (6.1.2.1)		A	Use of paleoclimate for environmental monitoring and forecasting	Scientific endeavours	Surface - subsurface
	Educational resource (6.1.2.1)		A	Use of geological and geomorphological features for educational purposes (e.g. sites for field trips)	Scientific endeavours and educational resources	Surface - subsurface

All services listed in Table 3 are, however, not necessarily relevant from a subsurface perspective. The structures and processes that deliver some services, such as provisioning of surface water resources for drinking, take place foremost at the surface, whereas other services, such as subsurface space, are intimately associated with the underground. From a broad subsurface planning perspective, it is desirable to delineate and highlight such services that originates from the subsurface to be able to better account for effects on said services due to subsurface projects (such as in the two theoretical projects presented in this thesis). As point of departure, 25 services, were listed in publication I as relevant form a subsurface perspective (these services are highlighted with bold in Table 3). These services are mainly derived from subsurface structures and processes (i.e., derived from deep-seated stocks) and includes examples from both definitions to fully reflect the wide range of services the abiotic nature provides. These subsurface services were selected from the reviewed literature based on the examples provided in these texts that relate to the subsurface. Although van Ree and van Beukering (2016) define geosystem services as “the goods and services that contribute to human welfare specifically resulting from the subsurface”, the bold marked services in Table 3 do not always coincide with services identified from literature aligning with definition B. Notably, this the list of geosystem services aligning with definition A is more detailed with regard to cultural and knowledge services. However, this is not to say that these services could not be conceptually included in definition B, but this was not explicitly mentioned in the reviewed literature.

4.2 Economic valuation of non-market geosystem services

Figure 7 shows the number of economic valuation studies identified in the reviewed literature that explicitly value changes in the supply of non-market geosystem services and ecosystem services as result of abiotic changes in the subsurface. Figure 7A shows that there are relatively few valuation studies (75 in total). Furthermore, the figure emphasises that some services have gained more attention in the reviewed literature than others. A majority of the studies found valued externalities related to provisioning services, and especially services related to provisioning (and to some extent regulating) of groundwater and geomaterials, which are the most studied ones. On the other hand, exceedingly few studies were found that relate to cultural and supporting services. The lack of studies on these services indicates that the entire multifunctionally of the subsurface and the non-market goods and services therein has not been valued in scientific literature. Furthermore, the rather substantial number of articles that value changes in supply of ecosystem services as result of abiotic changes in the subsurface (44%, 37 in total), highlights the difficulty in separating biotic and abiotic nature. There is often an overlap between the two, and changes to one might have implications for the other. One such example is the study by Mazzotta et al. (2015), in which they investigated the potential loss of welfare to freshwater anglers as a result of mountain top coalmining within West Virginia. Another example is the study by Hérivaux and Grémont (2019) in which they valued ecosystem services to argue for strategic groundwater preservation.

Figure 7B shows which valuation methods have been predominantly used in the reviewed literature. The most common valuation approaches are direct market and stated preference methods, accounting for 74% of the studies. Individually, the most used valuation method is contingent valuation (CV), followed by replacement costs (RC) and benefit transfer (BT). Despite the relatively few identified valuation studies, a wide set of valuation methods have been applied. This supports that the various approaches available to estimate WTP or WTA for ecosystems services are equally applicable to geosystem services.

The review however indicates some gaps: there are geosystem services that have received no attention at all in the reviewed literature, e.g., regulation of temperature by the subsurface and most of the cultural services. There are also relatively few studies in total, and the studies found tend to focus on reduced supply of services rather than increased or preserved supply. Altogether this suggest that the amount of available information from studies at a specific location that can be used to monetise services at another location with a similar context is limited. Nonetheless, there can be opportunities for value transfers for the more well-studied services, such as provisioning of groundwater and construction aggregates, for which there are more studies available.

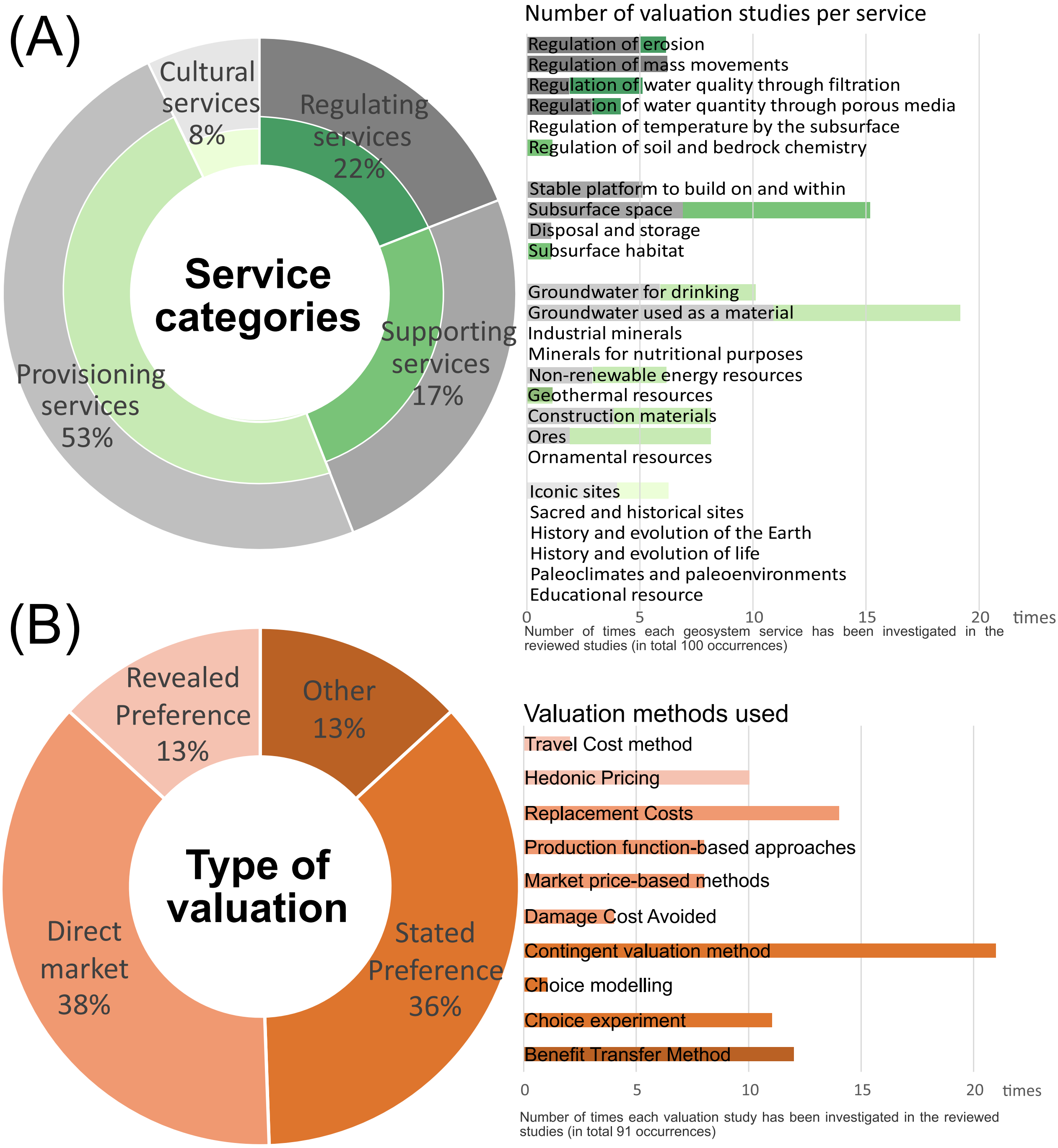

Figure 7: Illustration of search result from the systematic literature review. A) Number of valuation studies per service. Gray colour for changes in the supplied quantities of geosystem services and green colour ecosystem services due to changed subsurface abiotic structures and processes. B) Valuation methods applied to assess the services in A. Note that one or more services and methods might have been studied/employed in the same study. The data constituting the basis for the figure is based on 75 studies and presented in detail in appendices C and D.

4.3 CBA demonstration of two subsurface projects

The first step in setting up the basis for the CBA is to map out the services that was highlighted in publication I as relevant from a subsurface perspective and how changes to abiotic structures and processes within the subsurface due to the two projects would influence the supply of said services. Each effect was categorised for "negative effect", "positive effect", or "no effect". These categories imply cost items, benefit items or no effect in a CBA respectively. A fourth category, “negative or positive”, is used when there can be both negative and positive outcomes when comparing to the reference alternative. For example, there are examples of underground construction that damage or degrade sites of historical, recreational and sacred value (e.g. Qiao et al., 2022). Similarly, there are cases of when underground construction has also exposed historical, recreational and sacred sites so that they can be visited and/or be preserved for the future (e.g. Valdenebro et al., 2019).

The result of this mapping (presented publication II) was used as a basis for establishing benefit and cost items associated with the two cases, shown in Table 4. The reference alternative for Case 1 is that no new tunnel is constructed, and the traffic keeps using the existing road. The reference alternative for Case 2 is that no extraction is allowed and the glaciofluvial delta deposit is kept intact. Table 4 includes the changes to geosystem services that were identified in the systematic mapping of effects and additional societal costs and benefit items and is more detailed regarding benefits and costs due to the impacts on geosystem services, but other items such as decreased barrier effects above ground for fauna (B3) are also included.

Some items are shared between the two cases, as seen in Table 4. However, it is worth noting that although these items are shared, they might not be given the same weight in both cases. For example, extraction of geomaterials is a benefit item for both cases and reflects the main purpose of case 2 but is a side-effect in case 1. Furthermore, attention should be paid to the risk of double counting when identifying and quantifying the costs and benefits items. Some geosystem services might be intermediate in the production of a final service. For example, in both cases it is assumed that there will be a decreased capacity to regulate groundwater quantity and quality (C6 and C7), which in turn will presumably result in a decreased access to groundwater for extraction (C12) and have a negative impact on services provided by groundwater-dependent ecosystems (C17). Monetising access to groundwater for extraction (C12) and services provided by groundwater-dependent ecosystems (C17) will likely include effects on the capacity of the subsurface to regulate groundwater quantity and quality (C6 and C7). Managing such double-counting issues is essential for any CBA and more examples are possible although they are not necessarily illustrated in the table below. Nonetheless, these examples highlight that depending on the analytical context some services can be regarded as either intermediate or final services in themselves.

*Table 4: Benefit and cost items in a CBA of case 1 and case 2, respectively. Items which are about changed provision of geosystem services are indicated by geosystem services (GS). For each item, a check mark denotes in which NPV term(s) the item is found. Note that the check marks are only indicative, see text. The impact on the government's revenues and expenditures (simplified as ΔmL) is suppressed for simplicity. Benefit and cost items marked with **bold** are items for which valuation studies were found in the reviewed literature derived from the systematic search described in section 3.1.2 valuation of geosystem services.*

Item	Case 1	Case 2	Market goods included in $p\Delta x^s$ or ΔC	Non-market goods included in $w\Delta G(\Delta a_{sub})$	Non-market goods included in $w\Delta E(\Delta a_{sub})$	Other non-market goods
	Benefits					
B1	Improved transportation, e.g., reduced travel time and transport costs		✓			✓
B2	Improved traffic safety, e.g., reduced damage risks for vehicles and reduced morbidity and mortality risks		✓			✓
B3	**Decreased barrier effects above ground, e.g., improved mobility opportunities for humans and wildlife**		✓			✓
B4	**Improved health and environment due to reduced noise and decreased air emissions**					✓
B5	**Increased global climate regulation by reduction of GHG concentrations**					✓
B6	**Increased access to space above ground**					
B7 (GS)	**Increased access to underground space**		Assumed to be valued through items B1-B6			
B8 (GS)	**Revenues from extraction of geomaterials**		✓			
B9 (GS)	Gain of, or positive influence on, historical, recreational, and sacred sites			✓		
B10 (GS)	Gain of, or positive influence on, geoscientific and geoeducational resources			✓		
B11	Potential agglomeration economies, e.g., increased synergy opportunities for other actors		✓			✓

Item	Case 1	Case 2	Market goods included in $p\Delta x^s$ or ΔC	Non-market goods included in $w\Delta G(\Delta a_{sub})$	Non-market goods included in $w\Delta E(\Delta a_{sub})$	Other non-market goods
	Costs					
C1	Construction costs and other investment costs, and operation & maintenance (O&M) costs		✓			
C2		Closure costs	✓			
C3	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		✓			✓
C4	**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**					✓
C5 (GS)	Decreased capacity to regulate erosion and mass movements		Assumed to be valued through item C1			
C6 (GS)	**Decreased capacity to regulate groundwater quantity**		Assumed to be valued through items C12 and C15			
C7 (GS)	Decreased capacity to regulate groundwater quality		Assumed to be valued through items C12 and C15			
C8 (GS)	Decreased capacity to regulate temperature by underground thermal storage			✓		
C9 (GS)	**Decreased access to stable platform to build on and within**		✓	✓		✓
C10 (GS)	Decreased access to underground space			✓		
C11 (GS)	Loss of or negative influence on subsurface habitats			✓		
C12 (GS)	**Decreased access to groundwater for current and/or future extraction for drinking water or other purposes**		✓	✓		
C13 (GS)	Loss of, or negative influence on, historical, recreational, and sacred sites			✓		
C14 (GS)	Loss of, or negative influence on, geoscientific and geoeducational resources			✓		
C15	**Negative influence on ecosystem services in groundwater-dependent ecosystems, e.g., bioproduction capacity, recreational opportunities, capacity to capture CO_2**		✓		✓	
C16	**Decreased existence values and other non-use values associated with affected nature, e.g., biodiversity and geodiversity**			✓	✓	

The high level of aggregation of the cost and benefit items seen in Table 4 implies that many of the items contain both market goods and non-market goods. The market goods can be directly valued as they are traded at a market and Table 4 show that some geosystem services are used for commodities being traded at a market. One example is access to geomaterials, whose extraction typically gives rise to market goods such as sand and gravel (B6). A less straightforward example is access to groundwater (C12), whose extraction provides drinking water but also is essential for other services. For some of which there might be markets but also for other services which there are no forthright market e.g., facilitating groundwater-dependent ecosystems (C17). For these non-market goods in Table 4 monetary estimates can be derived through applying one or several of the valuation methods described in Section 2.5 (e.g. services that influence historical, recreational, and sacred sites, B7, C15). A more detailed description of the items, than is carried out here, could allow an unequivocal sorting into market goods and non-market goods. However, a detailed description was avoided for simplicity and to highlight the main message that a CBA of the two cases might provide a biased result if values of non-market goods are not included.

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5 DISCUSSION

This chapter presents a summary discussion on the geosystem services as a concept, their valuation and inclusion in cost-benefit analysis and what this implies.

5.1 Geosystem services definitions

Geosystem services as a concept is both appealing and challenging. On the one hand, as a general description and categorisation of benefits we as humans derive from abiotic resources in the subsurface, it raises awareness about otherwise potentially neglected resources and facilities easier communication among both subsurface experts and non-experts. On the other hand, it is by necessity a simplification of an interconnected and complex reality. Furthermore, the review of literature that deals with geosystem services show that what authors mean when they refer to, write about, or discuss geosystem services depends on to whom and what issue the authors are addressing. The difference between the two most common and prevailing definitions (definition A & B) is not only (geo-)spatial but also, in part, reflects a different approach to the interactions between abiotic and biotic nature. At least in part, these different approaches to interactions between abiotic and biotic nature showed in the two definitions of geosystem services arise from the complexity of separating biotic and abiotic structures and processes from each other. Fox et al. (2020) tries to acknowledge this difficulty in their suggested Geo-Eco Services Framework where ecosystem services are conceptualised as a result of biophysical structures and processes and can be driven either mainly by biotic or by geodiversity structures and processes (see Figure 5). However, they acknowledge that the line between abiotic and biotic is in best of circumstances blurred.

The ecosystem services concept is today firmly established in land and water management literature and practice. However, although nature is comprised of both biotic and abiotic elements, the abiotic services that are not usually traded on a market, such as some of the supporting or regulating services, are often omitted in these environmental studies (e.g. Gray, 2018; van Ree et al., 2017). This narrow focus on one part of nature (the biotic) fails to acknowledge the fundamental other parts (abiotic), which is unsatisfactory for management of (all) natural capital. Though not fully developed the concept of geosystem services has been put forward as a concept that can make these resources more visible and acknowledged (e.g. Gray, 2011, 2018; Norrman et al., 2021; van Ree & van Beukering, 2016; Volchko et al., 2020). The concept of geosystem services can be useful since it emphasises services of nature that are repeatedly overlooked in environmental frameworks. Furthermore, it can facilitate communication of said services across multiple scientific disciplines and stakeholders to better account for them in decisions on sustainable use of the subsurface.

However, a not trivial amount of work is left to provide a unified and coherent definition of geosystem services. The search for articles on geosystem services, furthermore, highlights the ambiguity surrounding the prefix geo-, that is used in a broad variety of contexts and the difficultly in pinpointing what a geosystem is or constitutes. For example, in physical geography discourses, a geosystem represents dynamic combinations of biotic, abiotic and anthropocentric factors occurring on planet Earth (e.g. Christopherson & Birkeland, 2018), whereas when geosystem and geosystem services is used in conjunction with satellite position technologies it refers to providing functionality in geo-positioning networks. The literature search highlights this difficulty when searching for studies on geosystem services, as defined in definition A or B, as out of the 2658 articles that the search returned with search string tailored to catch geosystem services, only 29 studies were found relevant and included in the final synthesis. However, it should be noted that there might be articles which have fallen outside of the literature search as: (i) the studies are reported in unindexed grey literature such as consultancy publications or governmental reports, or (ii) studies are reported in other languages than English.

5.2 Valuation of geosystem services

Placing a monetary value on services can highlight their importance, reveal the costs associated with their degradation, and facilitate communication, as most people are familiar with currencies. Similarly, the integration of ecosystem services into environmental accounting (e.g. the Common International Classification of Ecosystem Services (CICES), Haines-Young & Potschin-Young, 2018) have made the value of ecosystems visible and acknowledged in decision-making (e.g.Carpenter et al., 2009; Cornell, 2011). Environmental economic valuation methods to value non-market goods and services derived from ecosystems are available as a result of several decades of economic valuation research (Petrolia et al., 2021; Smith, 2006; Tinch et al., 2019). As seen in the review of valuation studies (Publication II), they are also employed for valuation of non-market goods and services derived from the subsurface as there are no theoretical hinders to use these generic methods for monetary valuation of geosystem services. However, the literature review also reveals that there is a scarcity of valuation studies in scientific literature that place an economic value on the changes in supply of non-market geosystem services (and ecosystem services) because of changes to the abiotic subsurface conditions due to human activity (in total 75 studies). Of all reviewed studies, services related to groundwater and geomaterials constituted 53%, while valuation studies of cultural geosystem services only constituted 8%. There can, however, be economic valuation studies of geosystem services which have fallen outside of the literature search as: (i) the keywords used in the search strings do not include all possible labels used for the selected geosystem services, (ii) the studies are reported in unindexed grey literature, or iii) the studies were not written in English. It should also be kept in mind that market goods and services were not targeted in the literature review. While valuation of geosystem services typically having a market price (such as commercial ores) was not a part of this study, it is still important to note that such market prices might be flawed from a societal point of view because of the presence of externalities not included in the market price (such as those caused by mining).

To be able to set up a CBA in which all relevant cost and benefits can be aggregated and compared, it is typically required that all benefits and costs are quantified and monetized. 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 constraints or financial limitations). To get around this issue, secondary data might be used by transferring information available from earlier studies already completed in another location or context (e.g. Richardson et al., 2015). However, the two main approaches to such a benefit transfer, value transfer and function transfer, require studies that are similar to the site or context that is to be valued. In other words, a broad library of valuation studies is often needed as each site and context is to some extent unique. The studies identified in the literature review as relevant for the two cases span a wide range of services and locations but few, if any, are enough similar in terms of location and context to be readily applicable for benefit transfer to the situations that the two cases represent.

Recent contributions to environmental accounting have stressed the need to focus on the final services (those contributing to benefits) rather than on intermediate services and ecosystem functions, as this decreases the risk of double counting (Pascual et al., 2010). The supporting services category is controversial in ecosystem services frameworks as these services may pose a risk of double counting when they serve as inputs to other ecosystem services, i.e. they are intermediate ecosystem services in the provision of final benefits (Jax, 2016; Potschin & Haines-Young, 2016; Rives et al., 2016). One solution to minimise this risk is to exclude supporting services from the classification, as is done in CICES for ecosystem services. The supporting services category is however included in both predominant definitions of geosystem services. The reason for their inclusion is that it has been argued (e.g. in Lundin Frisk et al., 2022; van Ree et al., 2017) that some supporting geosystem services are related to carrier functions of the geological substrate and thus are directly used to enhance human welfare (i.e., a final service). The carrier concept has been included in the classification of ecosystem services since the 1970s, referred to as functions of the natural environment for society (Braat et al., 1979; cited in van der Meulen et al., 2016a), stressing the importance of the geological substrate to provide services such as a medium for construction (supporting), extraction of minerals and other materials (provisioning), and energy and waste storage (regulating). These services were, however, excluded from later studies as focus shifted to the biotic part of nature and remain inconsistently included in natural capital and ecosystem services studies (Gray, 2018).

Regardless of if these supporting geosystem services are related to carrier functions, the CBA for the two cases highlights the difficulty in valuing services that can be viewed as both intermediate services and final services. In the hypothetical case 1, the benefits of using underground space for transport infrastructure is expected to be valued not as a final service itself, but rather as benefits derived from safer transportations, saving space aboveground etc (items B1 – B6 in Table 2). This indicates that including supporting geosystem services (such as space and stable platform to build upon) as final services in a CBA creates a risk for double counting. Issues of double counting belongs to the nitty-gritties of conducting a CBA and needs to be attended to in each specific application. However, it should be noted that supporting services are by definition excluded in CICES and it should be further investigated whether the supporting geosystem services can be reclassified not to be overlooked in environmental accounting. 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 stress and strain (distribute loads).

As a final note, mapping the effects on geosystem services resulting from the two subsurface projects, from a process-oriented perspective proved to be useful for setting up the basis for the CBA. The systematic mapping helped to unveil effects that otherwise could be hidden and unforeseen without a thorough investigation. The mapping using a process-oriented approach can be useful also in qualitative or semi-quantitative assessments aimed to support well-informed decisions on subsurface uses or within social and physical planning.

5.3 CBA as support for decisions regarding subsurface use

In this thesis the use of CBA is investigated to support sound strategic decisions regarding subsurface use. The two theoretical cases demonstrate that the projects are associated with effects on both market and non-market goods and services. The lack of a market for some of the geosystem and ecosystem services highlight that a CBA can give a more holistic support to decision-making than a financial analysis, which would only include goods and services traded on existing markets. Furthermore, a distributional analysis as part of a CBA can elucidate which groups in society are affected positively or negatively by a subsurface project.

However, setting up a CBA involves methodological challenges within its own theoretical framework. One such example is to select an appropriate social discount rate for comparing costs and benefits occurring in different points of time, especially if the cost or benefit stretches for into the future, for example by decreasing discount rates over time (Arrow et al., 2014). While the issue of accounting for costs and benefits stretching far into the future can be especially prominent in a CBA context, as it cannot be avoided in a calculation of a PV of future benefits and costs, it is an issue that is present in *all* decision-support methods that have to consider future effects and therefore what weight to place on future effects. Furthermore, a CBA cannot provide wider answers than what its ethical point of departure allows. A CBA relies on anthropocentric preference satisfaction consequentialism (Hausman et al., 2016; Perman et al., 2011) which can be contrasted to non-consequentialism represented by rights-based ethics and duty ethics, or a biocentric worldview in which humans are not given a greater intrinsic value than other species of organisms.

Over the last few decades, a substantial body of literature have been devoted to monetary valuation or "monetization" of the wide range of services provided to human societies by nature (e.g. Costanza et al., 1997; Costanza et al., 2014). Applying an economic thinking to nature have made the contribution of the biotic part of nature to human welfare more visible and accounted for in environmental polices (Carpenter et al., 2009; Pascual et al., 2010). However, referring to "what nature does for us" is a profoundly anthropocentric and utilitarian perspective that have received criticism (see e.g. Baveye et al., 2013; Cornell, 2011; Gatto & De Leo, 2000) as it implies that nature only has a value if it generates a service for humans and does not reflect the great diversity of values of nature that exists across the world's worldviews, cultures, knowledge system and disciplines (IPBES, 2022). Given the diversity of worldviews on value, it is challenging to define nature's value in a universal manner that is acceptable to all and in fact, what expression of value is, is an ongoing discourse (see e.g. Freeman et al., 2014) that yet have no clear answer. Furthermore, people place a WTP on services on the basis of what they consider is appropriate for them as individuals rather than on what is beneficial for society generally, as this choice is directly connected to, and constrained by, personal income. However, by taking the latter perspective, the same individual may consider the service' importance to humankind, which is not necessarily reflected in the individual WTP for this service and arrive at a different value. Another aspect is that both WTP and WTA depend on whether people are willing to value said services , which may not always be the case. Moreover, it is debated whether the interests of future generations are adequately represented in a CBA (Hausman et al., 2016).

5.4 Wider implications

The concept of geosystem services has the potential to support subsurface planning and to challenge the prevailing first-come-first-served principle to accessing the resources in the subsurface by: (1) providing a basis for a common understanding of the subsurface as a multifunctional resource, and (2) supporting an inventory of multiple subsurface resources through mapping of geosystem services – including their identification, quantification and valuation – and (3) identification of potential conflicts and synergies between them. Using a framework such as geosystem services to classify the services that stem for the often 'invisible' subsurface, allow these services to be systematically inventoried in a transparent way which that can be acceptable to all stakeholders that may have different levels of proficiency in geosciences. Using geosystem services as a framework to systematically map effects of subsurface projects using a process-oriented perspective proved to be useful for describing the full range of (negative and positive) effects these projects may have on future supply of subsurface resources (publication II). This, in turn, can lower the risk of, or avert developments where, one subsurface use results in untended disruption to other geosystem and ecosystem services and severely limit the benefits society might otherwise derive from the subsurface.

The review of literature related to geosystem services (publication I) is indicative of that a unified definition could indeed be beneficial in communicating the importance of these services to decision-makers, policymakers, and the general public as a systematic inventory can increase the understanding of both the opportunities as well as the constraints or risks associated with the subsurface. However, it remains a non-trivial endeavour to unify and harmonise the geosystem services concept and terminology.In publication I it was suggested that such an endeavour could mimic the CICES approach to ecosystem services where the definition of each class of services consists of both an "ecological clause", describing the biophysical output, and a "use clause", describing the contribution to an eventual benefit. However, to make the definitions more operational, such structure ought to be complemented with tangible examples of specific geosystems services in a wider range of analytical contexts.

Furthermore, the work carried out in this thesis also highlights that geosystem services as a concept can be used to raise awareness and integrate various perspectives or disciplines into environmental management (i.e. functioning as a boundary object), similar to how ecosystems services have been integrated into environmental accounting using monetary valuation (e.g. the Common International Classification of Ecosystem Services (CICES), Haines-Young & Potschin-Young, 2018; Haines-Young & Potschin, 2010, 2011, 2012), potentially supporting “a better integration of environmental sciences and cross disciplinary conversations”(Hale et al., 2021, p. 4198). While monetizing nature is without doubt difficult, uncertain and associated with moral value statements (e.g. Hausman et al., 2016), it is something that is consciously (or unconsciously) done on a daily basis whenever politicians, governmental agencies, municipalities, businesses and individuals take decisions. By placing a monetary value on services provided by nature, this choice can be made explicit, allowing for transparency and informed trade-offs. Decisions on services provided by nature are often, explicitly or implicitly, based on a rather narrow set of values (values as traded in markets) supporting short-term economic growth which do not necessarily reflect their total economic value (IPBES, 2022). However, by quantifying the value of geosystem services in monetary units, useful information on their total economic value is available to policymakers and can thus give a basis for well-founded decisions – making the trade-offs of their loss, depreciation or degradation in return for net gains explicit on the society-wide level.

As stated earlier in the discussion, the application of CBA for subsurface projects can provide a solid basis for a well-founded decision from a consequentialist view if a full quantification and monetisation of relevant cost and benefits items is possible. However, the discussed theoretical and ethical limitations of CBA highlight that a CBA analysis on its own may not be sufficient to answer the wide array of questions regarding subsurface use and emphasise the need for complementary types of analyses that in conjunction can capture the large diversity of values of nature to a greater degree (IPBES, 2022). One such example is multi-criteria analysis (MCA) in which information on various values can be integrated (Rosén et al., 2015; Saarikoski et al., 2016; Termansen et al., 2022). However, no analysis provides a panacea – a multi-criteria analysis is not more informative than the criteria being selected, and a deliberative approach will include decisions about whom are to be included in the deliberation and how. Nevertheless, using a structured framework and a systematic evaluation of effects on future supply of geosystem services, gives the opportunity to explicitly discuss theoretical-ethical limitations and model uncertainties, as well as facilitating communication across multiple scientific disciplines and stakeholders.

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6 CONCLUSIONS

This chapter presents a summary of conclusions from the appended papers.

The main conclusions from this thesis are as follows:

- There are two predominant definitions of geosystem services in scientific literature. In the first definition (A), geosystem services are abiotic services that are the direct result of the planet's geodiversity, independent of the interactions with biotic nature and there is no differentiation between suprasurface and subsurface features. In the second definition (B), geosystem services are considered to be only the goods and services that contribute to human welfare specifically resulting from the subsurface.

- A unified definition of geosystem services is desirable and as a suggestion to explore further, the work on a unified definition 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 human welfare in terms of benefits.

- If geosystem services are to be included CICES, supporting services are by definition excluded and it should therefore be further investigated whether these should be reclassified. 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 stress and strain (distribute loads).

- The CBA of the two cases highlight that careful attention to if and when a geosystem service is an intermediate service or a final service in a specific context is crucial, not least regarding supporting and regulating geosystem services.

- The review of valuation studies reveals that economic valuation of non-market geosystem goods and services is possible using established valuation methods. Studies on monetary valuation of geosystem goods and services are however scarce in scientific literature, especially regarding cultural geosystem services.

- Systematic mapping of effects on multiple geosystem goods and services caused by subsurface projects using a process-oriented perspective can make the consequences of such projects more visible and combined with a distributional analysis as part of a CBA, it can elucidate which groups in society are affected positively or negatively by a subsurface project. However, a CBA cannot capture the values outside its theoretical and ethical framework and as such there is a need for complementary types of analyses that together might better capture the large diversity of values of nature.

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7 ONGOING AND FUTURE WORK

The final chapter of the thesis presents issues that require further investigation and future work in the PhD-project.

The overall aim of this thesis was to explore the concept of geosystem services and investigate if it can support subsurface planning. An initial overview of the concept is presented here in the thesis, but the discourse surrounding the concept is ongoing and rapidly evolving. Nonetheless, there are as indicated in this thesis aspects that need further development. One such aspect is working on a unified definition of geosystem services and possibly establishing an abiotic parallel to the "ecological clause", describing the physical output, and a "use clause". This would be an interesting development and could be desirable both from a conceptual and environmental accounting point of view. It would however require a substantial effort spanning several multidisciplinary multiple scientific disciplines and is out of scope for this project.

The continuation of this PhD research project on developing thematic information that can support working with geosystem services in a planning context in Sweden and beyond. This will include, but is not limited to:

1. Investigating at which planning level (comprehensive, detailed, project) the different types of geosystem services are best managed within the Swedish planning system. Following the hypothesis that in general, the earlier in the planning process subsurface information is included, the better. However, data availability, scale and uncertainty will influence if and how effective such subsurface information can be handled at different planning levels.

2. Developing thematic information specifically adopted to support spatial planning above and below ground. Thematic maps or models can be based on geological information to deliver spatial information about the subsurface and its resources, e.g., geosystem services provided by the geological substrate. However, for thematic maps or models to be useful for planners, it is required that they are communicated and made available to actors and stakeholder that may not have an extensive background in within this scientific field.

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