THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Geosystem Services to Support Planning and Management of the Subsurface

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ABSTRACT

The subsurface is a critical yet often overlooked component of resilient societies. Despite its importance, the subsurface is often subject to fragmented and poorly coordinated use and management. This thesis explores the concept of geosystem services as a framework for recognising the subsurface's contributions to human welfare and integrating them into spatial planning. The thesis makes four key contributions: (1) it reviews existing definitions of geosystem services and their relevance to subsurface planning; (2) it reviews various methods for valuing these services and presents a framework for systematically including them when assessing the effects of subsurface projects; (3) it proposes a set of indicators for spatially assessing geosystem service potential; and (4) it develops a framework for creating thematic maps to visualise these services. The concepts, methods, and frameworks presented in this thesis have been tested across various spatial scales and contexts to evaluate their applicability. The results offer insights into how subsurface planning could benefit from a systematic integration of geosystem services. Collectively, the studies represent an initial step towards establishing common standards and procedures essential for operationalising this emerging field.

SAMMANDRAG

Undermarken är en viktig för att skapa hållbara och resilienta städer. Trots sin betydelse är användning och planering av undermarken dock fragmenterad och dåligt koordinerad. Denna avhandling tar avstamp i begreppet geosystemtjänster som ett sätt att öka medvetenheten om undermarken och dess betydelse genom att belysa undermarkens processer och strukturer som bidrar till människors välfärd. Avhandlingen och de artiklar som ingår bidrar till diskursen omkring undermarken och geosystemtjänster genom det följande: 1) en översikt av befintliga definitioner av geosystemtjänster och hur begreppet kan relateras till planering av underjorden, 2) en genomgång av olika metoder för att värdera dessa tjänster samt ett ramverk för att systematiskt inkludera dem vid bedömning av effekter som en konsekvens av undermarksprojekt, 3) en uppsättning indikatorer för geosystemtjänster för att spatialt bedöma potentialen för sådana tjänster, och 4) ett ramverk för att utveckla tematiska kartor som visualiserar geosystemtjänster. De koncept, metoder och ramverk som presenteras i denna avhandling har testats i olika skalor och sammanhang för att utvärdera deras tillämpbarhet. Resultaten från avhandlingen och artiklarna däri visar på hur planering av undermarken skulle kunna dra nytta av en systematisk integrering av geosystemtjänster. Tillsammans utgör studierna i denna avhandling ett tidigt steg mot att etablera standarder och rutiner, vilket är avgörande för att operationalisera den växande kunskapsbasen om geosystemtjänster.

LIST OF PUBLICATIONS APPENDED TO THE THESIS

This thesis is based on the following papers, referred to by Roman numerals in the text.

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

II. Lundin-Frisk, E., Söderqvist, T., Merisalu, J., Volchko, Y., Ericsson, L. O., & Norrman, J. (2024). Improved assessments of subsurface projects: Systematic mapping of geosystem services and a review of their economic values. *Journal of Environmental Management*, 365, 121562. https://doi.org/10.1016/j.jenvman.2024.121562

III. Lundin-Frisk, E., Ericsson, L. O, Lindgren, P., Melgaço, L., Mossmark, F., Sandström, O. T., ... & Norrman, J. (2025). Geosystem Services from the Subsurface: a Literature Review and a Proposed Set of Indicators Tailored to a Swedish setting. *Environmental and Sustainability Indicators*, 26, 100609. https://doi.org/10.1016/j.indic.2025.100609

IV. Lundin-Frisk, E., Lindgren, P., Taromi Sandström, O., Toft, E., Melgaço, L. Mossmark, F., Söderqvist, T., Volchko, Y., Melo Zurita, M. D. L., & Norrman J. (2025). Mapping Geosystem Services Potential for Urban Climate Resilience: a Case Study from Malmö, Sweden [Manuscript submitted for publication]. Department of architecture and civil engineering, Chalmers University of Technology.

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MY CONTRIBUTION TO THE PUBLICATIONS

Table I provides an overview of my contributions and the division of labour among the coauthors for **Publications I-IV**. This overview adheres to the CRediT (Contributor Roles Taxonomy) guidelines and highlights the contributions made by each participant. The CRediT statements were submitted during the submission process for each publication and thus also appears in the published papers.

Table I: Division of work between the authors (CRediT author statement) for publications I-IV.

Description		**Publication**			
		I	**II**	**III**	**IV**
Conceptualisation	Ideas; formulation or evolution of overarching research goals and aims	**E.L-F.,** G.B., C.C., L.O.E., A.L., L-O.L., F.M., O.T.S., T.S., Y.V., J.N.	**E.L-F.,** L.O.E., J.M., T.S, Y.V., J.N.	**E.L-F.,** L.O.E., F.M., V.S., J.N.	**E.L-F**., P.L., O.T.S., E.T., L.M., F.M., J.N.
Data curation	Management activities to annotate (produce metadata), scrub data and maintain research data	**E.L-F.**	**E.L-F.,** L.O.E., J.M., T.S, Y.V., J.N.	**E.L-F.**	**E.L-F.**
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyse or synthesise study data	**E.L-F.**	**E.L-F.,** L.O.E., J.M., T.S, Y.V., J.N.	**E.L-F.**	**E.L-F.**
Funding acquisition	Acquisition of the financial support for the project leading to this publication	L.O.E., J.N.	L.O.E., J.N.	P.L., L.M., F.M, O.T.S, V.S., T.S., Y.V., M.M.Z, J.N.	P.L., L.M., F.M, O.T.S, V.S., T.S., Y.V., M.M.Z, J.N..
Investigation	Conducting research and investigation process, specifically performing the experiments, or data/evidence collection	**E.L-F.**	**E.L-F.,** L.O.E., J.M., T.S, Y.V., J.N.	**E.L-F.,** L.O.E., P.L., F.M., O.T.S, V.S., J.N.	**E.L-F**., P.L., O.T.S., E.T., L.M., F.M., J.N.
Methodology	Development or design of methodology; creation of models	**E.L-F.,** Y.V., J.N.	**E.L-F.,** L.O.E., J.M., T.S, Y.V., J.N.	**E.L-F.,** L.O.E., F.M., V.S., J.N.	**E.L-F.**
Project administration	Management and coordination responsibility for the research activity planning and execution	J.N.	J.N.	J.N.	J.N.
Supervision	Oversight and leadership responsibility for the research activity planning and execution	L.O.E., Y.V., J.N.	L.O.E., Y.V., J.N.	L.O.E., Y.V., J.N.	L.O.E., Y.V., J.N.
Validation	Verification of the overall replication/ reproducibility of results/experiments and other research outputs	*N/A*	*N/A*	*N/A*	**E.L-F.**
Visualisation	Preparation, creation and/or presentation of the published work, specifically visualisation/data presentation	**E.L-F,** L.O.E., J.N.	**E.L-F.,** L.O.E., J.M., T.S, Y.V., J.N.	**E.L-F.**	**E.L-F.**
Writing – Original Draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft	**E.L-F.,** Y.V., J.N.	**E.L-F.,** L.O.E., J.M., T.S, Y.V., J.N.	**E.L-F.**	**E.L-F.**
Writing – Review & Editing	Preparation, specifically critical review, commentary or revision – including pre- or post-publication stages	**E.L-F.,** G.B., C.C., L.O.E., A.L., L-O.L., F.M., O.T.S., T.S., Y.V., J.N.	**E.L-F.,** L.O.E., J.M., T.S, Y.V., J.N.	**E.L-F.,** L.O.E, P.L., L.M., F.M, O.T.S, V.S., T.S., Y.V., M.M.Z, J.N.	**E.L-F**., P.L., O.T.S., E.T., L.M., F.M. T.S., Y.V., M.M.Z., J.N.

Authors are placed in alphabetical order except for thesis author (placed first) and main supervisor (placed last). **E.L.F:** Emrik Lundin Frisk, **G.B:** Göran Blom, **C.C:** Christel Carlsson, **L.O.E:** Lars O. Ericsson, **A.L:** Andreas Lindhe, **L.O.L:** Lars-Ove Lång, **P.L.:** Paula Lindgren, **LM:** Lorena Melgaço, **JM:** Johanna Merisalu, **FM:** Fredrik Mossmark, **OTS:** Olof Taromi Sandström, **VS:** Victoria Svahn, **TS**: Tore Söderqvist, **YV:** Yevheniya Volchko, **MMZ:** Maria de Lourdes Melo Zurita, **JN:** Jenny Norrman

LIST OF PUBLICATIONS NOT APPENDED TO THE THESIS

List of different publications that are not part of the thesis.

Scientific or popular science articles:

- Norrman, J., Taromi Sandström, O., Melo Zurita, M. D. L., Mossmark, F., Lundin-Frisk, E., Melgaço, L., … & Victoria Svahn (2024). Deep planning: improving underground developments through inter- and transdisciplinary collaboration. *European Geologist*, 57. https://doi.org/10.5281/zenodo.12205943

- Melo Zurita, M. D. L., Melgaço, L., Norrman, J., Lundin-Frisk, E., Volchko, Y., Söderqvist, T., … & Mossmark, F. (2024). Governing urban lands from the bottom down – Subsurface inclusion in spatial planning. *Urban Matters.* https://urbanmattersjournal.com/governing-urban-lands-from-the-bottom-down-subsurface-inclusion-in-spatial-planning/

- Melgaço L., Melo Zurita, M. D. L., Taromi Sandström, O., Norrman J., Volchko, Y. Lundin-Frisk, E., … & Coyne, T. (2025). Inscrutable knowings and inscrutable spaces–undergrounds as risk. [Manuscript submitted for publication]. Lund university.

Conference papers and extended abstracts in conference proceedings:

- Mossmark, F., Lindgren, P., Lundin-Frisk, E., Melgaço, L., Melo Zurita, M. D. L., Norrman, J., ... & Volchko, Y. (2023). Case Study-Driven Research to Provide a Foundation for Advancing Geosystem Services and Planning Practices for the Subsurface. In *Conference of the Associated research Centers for the Urban Underground Space* (pp. 529-534). Singapore: Springer Nature Singapore.

- Volchko, Y., Söderqvist, T., Lundin-Frisk, E., Lindgren, P., Melgaço, L., Melo Zurita, M. D. L. & Norrman, J. (2023). Geosystem Services for Subsurface Planning in Sweden: A Pilot Survey. In *Conference of the Associated research Centers for the Urban Underground Space* (pp. 1181-1184). Singapore: Springer Nature Singapore.

- Svahn, V., Norrman, J., Lundin-Frisk, E., Volchko, Y., Melgaço, L., Melo Zurita, M. D. L., ... & Söderqvist, T. (2025). Geosystem services as the basis for subsurface impact assessment of alternative railway tunnel corridors. In *Tunnelling into a Sustainable Future–Methods and Technologies* (pp. 1867-1874). CRC Press.

- Mossmark, F., Norrman, J., Lindgren, P., Lundin-Frisk, E., Melgaço, L., Melo Zurita, M., ... & Volchko, Y. (2024). UNDER: Geosystem services underneath for sustainable communities and improved spatial planning practices. In *EGU General Assembly Conference Abstracts* (p. 20734).

Licentiate thesis:

- Lundin-Frisk, E. (2023). Geosystem services to support decisions on subsurface use. (Chalmers University of Technology: 2023:1) [Licentiate thesis, Chalmers University of Technology]. Chalmers University Publications Electronic Archive. https://research.chalmers.se/publication/534818/file/534818_Fulltext.pdf

ABBREVIATIONS AND ACRONYMS USED IN THE THESIS

Table II introduces the abbreviations and acronyms used in the thesis.

Table II: Abbreviations and acronyms used in the thesis

Abbreviation or acronym	Word or phrase
AP-RMSE	Average Pairwise Square Root Mean Error
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
ESC	Ecosystem Services Cascade
GS	Geosystem Services
GSC	Geosystem Services Cascade
HP	Hedonic Pricing
MA	Millennium ecosystem Assessment
MCA	Multi-Criteria Analysis
MDI	Map Disagreement Index
MP	Market Price-based methods
NA-RMSE	Range-based Normalized Average Square Root Mean Error
NPV	Net Present Value
OFAT	One-Factor-At-a-Time
PF	Production Function-based approaches
PV	Present Value
RC	Replacement Cost methods
RCP 8.5	Representative Concentration Pathway 8.5
RCP 4.5	Representative Concentration Pathway 4.5
TC	Travel Cost method
TEEB	Economics of Ecosystems and Biodiversity
TEV	Total Economic Value
TM	Thematic Map
SM	Supplementary Materials
WSS	Water System Services
WTA	Willingness To Accept
WTP	Willingness To Pay

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Chapter 1
INTRODUCTION

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

1.1 Background

The subsurface, although often absent from everyday awareness, is the foundation upon which all human infrastructure relies (Dick et al., 2017; van der Meulen et al., 2016b). It is a multifunctional resource; providing water, energy, and materials, habitats for ecosystems, supporting surface life, and serves as a repository for cultural and geological heritage (van Ree & van Beukering, 2016; Volchko et al., 2020). Despite its importance, the subsurface is often subjected to poorly planned and uncoordinated use. The principle of 'first-come, first-served' often governs access to subsurface resources, leading to conflicts between short-term and long-term uses and hindering sustainable development (Admiraal & Cornaro, 2016; Bobylev, 2009; Dick et al., 2017; Stones & Heng, 2016; Tengborg & Sturk, 2016). These tensions are exacerbated by the hidden nature of the subsurface and the permanence of many claims (viewed on a human timescale) which can result in unintentional outcomes where individual projects dictate future uses, highlighting the need for long-term strategic planning (de Mulder et al., 2012; Dick et al., 2017; Norrman et al., 2021; van der Meulen et al., 2016b; van Ree & van Beukering, 2016).

While long-term strategic planning is essential, urban planners are often unaware of the wealth of information available about the subsurface, and subsurface specialists may neither understand how planners would use such information if it was accessible (Dick et al., 2017) or have developed datasets or tools that are sufficiently accessible to planners. This disconnect can result in missed opportunities for more integrated and informed urban development. Bridging this gap requires not only improved communication between disciplines but also the development of tools and frameworks that can translate subsurface data into formats that are meaningful and actionable for planners. To address these challenges, the concept of geosystem services has been proposed. Geosystem services are benefits to human welfare derived from the abiotic environment (Gray, 2013) or the subsurface (van Ree & van Beukering, 2016). This concept builds on the well-established framework of ecosystem services, which has brought attention to the benefits humans derive from nature, focusing on biotic nature[1]. While ecosystem services are widely accepted and integrated into global and national environmental policies (Carpenter et al., 2009; Cornell, 2011; Geneletti, 2016), they

[1] Labelled as the biophysical part of nature in the latest revision of CICES, version 5.2. See Haines-Young (2023) for details.

generally do not fully capture the subsurface nor abiotic aspects (e.g. Gray, 2018; van Ree et al., 2017; van Ree et al., 2024).

The concept of geosystem services aims to fill this gap by making these subsurface (or abiotic) resources more visible and acknowledged in decision-making and impact assessments. However, the concept remains loosely defined and is applied inconsistently across different contexts (see e.g. Chen et al., 2024; Gray, 2011; Sochava, 1975; van Ree & van Beukering, 2016). Nevertheless, some efforts have been made to delineate and operationalise the concept, which is crucial for its practical application (e.g. Finesso & Van Ree, 2022; Gray, 2018; Tognetto et al., 2021; van Ree et al., 2024). Establishing a clearer and more consistent definition could support interdisciplinary collaboration and enhance its relevance and usability for integrating the subsurface in planning processes.

In the context of spatial planning, maps are fundamental tools that provide a spatial framework for analysing land use, infrastructure, environmental conditions, and risk zones (Hillier, 2017; Wood, 2010), and they are deeply embedded in the daily routines of planners as familiar and accessible instruments for decision-making. Developing maps for geosystem services therefore has considerable potential to enhance planning processes by offering an intuitive and straightforward means of communicating complex interactions between resources across different spatial and temporal scales (see e.g. Burkhard et al., 2013; Cowling et al., 2008 refering to ecosystem services). Such maps can visualise spatial congruence or mismatches between the supply, flow, and demand of services, as well as the beneficiaries receiving them (Maes et al., 2016 refering to ecosystem services). Despite this potential, examples of geosystem service maps remain scarce, with Tognetto et al. (2021) among the few notable cases, and studies addressing their implementation in planning contexts are similarly limited.

1.2 Aim and Objectives

The overall aim of this thesis is:

> *to review geosystem services as a concept and investigate how it could contribute to an improved planning of subsurface usage.*

To reach the overall aim, the thesis has the following specific objectives, with roman numbers indicating in which appended publication the objective is addressed:

i. *to review definitions of geosystem services and identify those relevant for subsurface planning (I, II),*

ii. *to develop a method for systematic identification and assessment of the effects on geosystem services caused by subsurface projects and translate such information into a qualitative cost-benefit analysis (CBA) context (II),*

iii. *to compile valuation studies that have explicitly valued changes to the supply of geosystem services (II),*

iv. *to develop indicators that can be used to spatially assess and visualise the potential for delivering specific geosystem services related to the subsurface (III, IV), and*

v. *to develop maps of geosystem services potential and to investigate their usability and added value in planning, such as in the context of climate resilience planning (IV).*

1.3 Scope of Work

This thesis explores the concept of geosystem services, focusing on their definition, valuation, and relationship to the subsurface and its geophysical environment. It further explores the operationalisation of the concept to support planning, and the methods used to map and visualise geosystem services. To achieve the aim and fulfil the specific objectives of this thesis, a multi-disciplinary approach was required. To establish the context of the research, the thesis begins with an introductory chapter that outlines the background and rationale for the study (Chapter 1). This is followed by a theoretical background that expands on ecosystem services, geodiversity, geoconservation and subsurface planning to provide the necessary context for comparing and discussing geosystem services (Chapter 2). Chapter 3, the methodology chapter, describes the research process and the principal methods employed to address the research objectives. Chapter 4 presents a summary of the key findings from **Publications I–IV**, highlighting how each contributes to the overarching aim of the thesis. The subsequent chapter (Chapter 5) expands the discussion by including practical aspects of implementing geosystem services, and also highlighting specific domains where additional research is necessary to advance the field. The final chapter (Chapter 6) synthesises the main conclusions drawn from the thesis and the included publications, offering a concise reflection on the overall contributions of the works. This thesis also contains some material that has been published previously in the author's licentiate thesis (Lundin Frisk, 2023).

1.4 Limitations

The main limitations of this thesis are:

a. The multidisciplinary approach required linking different scientific schools, rather than an in-depth exploration of each topic. By necessity, this has resulted in limited investigations into each individual topic, and therefore, some information or context may be missing.

b. Describing nature in terms of services is a simplification of a complex reality where different components coexist and interact. This complexity is acknowledged, but some information or context related to each geosystem service and/or site may be missing.

c. Generalisations are made in publications forming the foundation of this thesis. It is acknowledged that actual application in for example a planning context is a setting-specific process that may require more detailed information and in-depth knowledge of site conditions than presented here.

d. Only beneficial processes and structures (referred to as services) are directly considered in this thesis. Processes that are disadvantageous, referred to as risks or disservices, such as the formation of radon from uranium-bearing rocks, are only indirectly considered. Nonetheless, these disservices are important to acknowledge from a planning perspective.

e. Only a limited number of reports have been reviewed in this study. It is acknowledged that additional relevant reports may exist; however, due to the absence of a standardised method for locating, accessing, and retrieving such documents, it has not been feasible to include them in the present work.

f. This study has primarily drawn upon literature written in English, with the inclusion of a limited number of reports in Swedish, Norwegian, and Danish. It is recognised that there exists relevant material discussing the definition and application of the geosystem concept in other languages, such as Russian, Chinese and Spanish. However, these sources have not been considered in the present work, largely due to linguistic constraints.

Limitations related to specific methods and/or type settings are discussed when presented in the thesis.

Chapter 2
THEORETICAL BACKGROUND

The concept of geosystem services emanates from the foundational work on ecosystem services. This chapter therefore begins by outlining the principles of ecosystem services (ES) and the methodologies employed in their valuation. This overview provides the necessary context for comparing and discussing geosystem services in relation to ecosystem services in the chapters that follow.

2.1 Introduction to the concepts Geodiversity, Geoheritage, Geoconservation and Geotourism

While biodiversity, the diversity of life, has long dominated conservation efforts, its abiotic counterpart, geodiversity, began gaining recognition in the early 1990s. The term was formally introduced in 1993, following the 1992 Rio Earth Summit and the adoption of the Convention on Biological Diversity (Brilha et al., 2018). It describes the natural variety of geological, geomorphological, soil[2], and hydrological features that form Earth's physical environment (Gray, 2011).

As interest in geodiversity grew, researchers such as Brilha et al. (2018), Hjort et al. (2015) and Gray (2013) emphasised that this diversity deserves conservation not only for its ecological role but also for its intrinsic value. However, within this diversity, certain features, such as unique rock formations, fossil sites, or striking landforms, stand out for their scientific, educational, cultural, or aesthetic significance. These features, have been referred to as geosites or geoheritage (Brilha, 2016). These can for example, include fossil beds, unique rock formations, volcanic landscapes, or glacial features that tell the story of Earth's history and the processes that have shaped this history (Brilha, 2016; Gray, 2011). Worth noting is that geoheritage also includes displaced elements such as minerals, fossils, and rocks preserved in museum collections, which retain their value despite being removed from their original context (Brilha, 2016).

Recognition of geosites and geoheritage is tied to the emergence of geoconservation, a field focused on protecting geological features, processes, sites, and mineral and/or rock specimens (Pescatore et al., 2023). Although geoconservation has not yet reached the visibility of biodiversity conservation, its importance is increasingly acknowledged. For example, recent studies highlight how geodiversity assessments can inform sustainable land planning, as demonstrated by Scammacca et al. (2022) in French Guiana and how participatory approaches can support geosystem services mapping, as shown by Stanley et al. (2023) in Virginia, United States of America (USA). In countries like the United Kingdom (UK), Sweden and Norway, national initiatives such as Sites of Special

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

Scientific Interest (SSSIs) and geological heritage sites (in Swedish: 'geologiskt arv'), along with international efforts like UNESCO-designated Geoparks, have helped establish a framework for conserving geologically significant sites (Gordon & Barron, 2013; Lundqvist & Dahl, 2020).

Building on the foundation of geoheritage and geoconservation, geotourism emerged as a field focused on how people engage with the geological character of places through travel (Ollier, 2012). Whether it involves collecting fossils on the Isle of Wight, exploring lava tubes in Iceland, or admiring the hydrothermal features of Yellowstone National Park, these experiences are deeply rooted in the unique geological or geomorphological attributes of each site. In many cases, the primary motivation for visiting these locations is directly linked to their distinctive Earth science features, which may offer both educational value and aesthetic appeal.

2.2 Definition and a History of the Concept of Ecosystem Services

Ecosystem services (ES) are the many and varied contributions to human welfare provided by ecosystems (Millennium Ecosystem Assessment, 2005). The concept emerged prominently in the late 20th century as a framework to articulate the value of nature in economic, social, and environmental terms, particularly in the context of sustainable development and environmental policy (Costanza et al., 2017; Gómez-Baggethun et al., 2010).

The Millennium Ecosystem Assessment (2005) (MA) played a pivotal role in formalising the ecosystem services framework, highlighting the extent to which human well-being is dependent on healthy ecosystems (Carpenter et al., 2009). Since then, the concept has been widely adopted in environmental management, land-use planning, and policy-making (Carpenter et al., 2009; Cornell, 2011; Geneletti, 2016). It provides a structured approach to assess trade-offs in ecosystem service use, promote conservation, and integrate ecological considerations into economic and social decision-making.

In the MA framework four categories of ecosystem services are classified, 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. It should be noted 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 pollutants from the 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.

Two other frameworks moulded the concept of ecosystem services as it known today; the Economics of Ecosystems and Biodiversity (TEEB) and the Common International Classification of Ecosystem Services (CICES).

The 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 multiple scientific disciplines and international and national policies. The initiative was launched in 2007, and its main motive was to establish global standard for natural capital[3] 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).

The CICES framework was developed from the work on environmental accounting initiated by the European Environment Agency (EEA) with consultation from the international scientific 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 has recurrently been revised over the last decade. In the latest revision, V5.2, the services that relate to abiotic nature, including many of the geological, hydrological and geomorphological structures and processes, have been relabelled as geophysical services (Haines-Young, 2023). In the CICES framework, the ecosystem services are linked to the needs 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 cascade model in Figure 1. The cascade model disentangles ecosystem services into a (bio)physical supply part (the environment) and a societal demand part (the social and economic system). This illustrates that a given environment holds certain potential to deliver a service that can fulfil societal needs and offer benefits (Albert et al., 2016; Andersson-Sköld et al., 2018; Burkhard et al., 2014; Potschin & Haines-Young, 2016).

By framing nature's contributions in terms of services, the ecosystem services concept bridges ecological science and human development, offering a rationale for the protection and sustainable use of ecosystems (Carpenter et al., 2009). It has also served

[3] Natural capital refers to the world's stocks of natural assets, including geology, soil, air, water, and all living organisms, which provide humans with a wide range of services (see Costanza, et al. 1997)

as a foundation for emerging frameworks, such as geodiversity, geosystem services and water system services which seek to complement and extend the understanding of nature's value by incorporating various geophysical components of the environment (Gärtner et al., 2022; Gray, 2011; van Ree & van Beukering, 2016). That said, a common criticism of the ecosystem services concept is its anthropocentric focus, which prioritises human benefits and often overlooks the intrinsic value of nature (Schröter et al., 2014). This perspective can lead to the marginalisation of ecological processes and species that do not directly serve human interests, potentially undermining conservation efforts and ethical considerations (e.g. Silvertown, 2015).

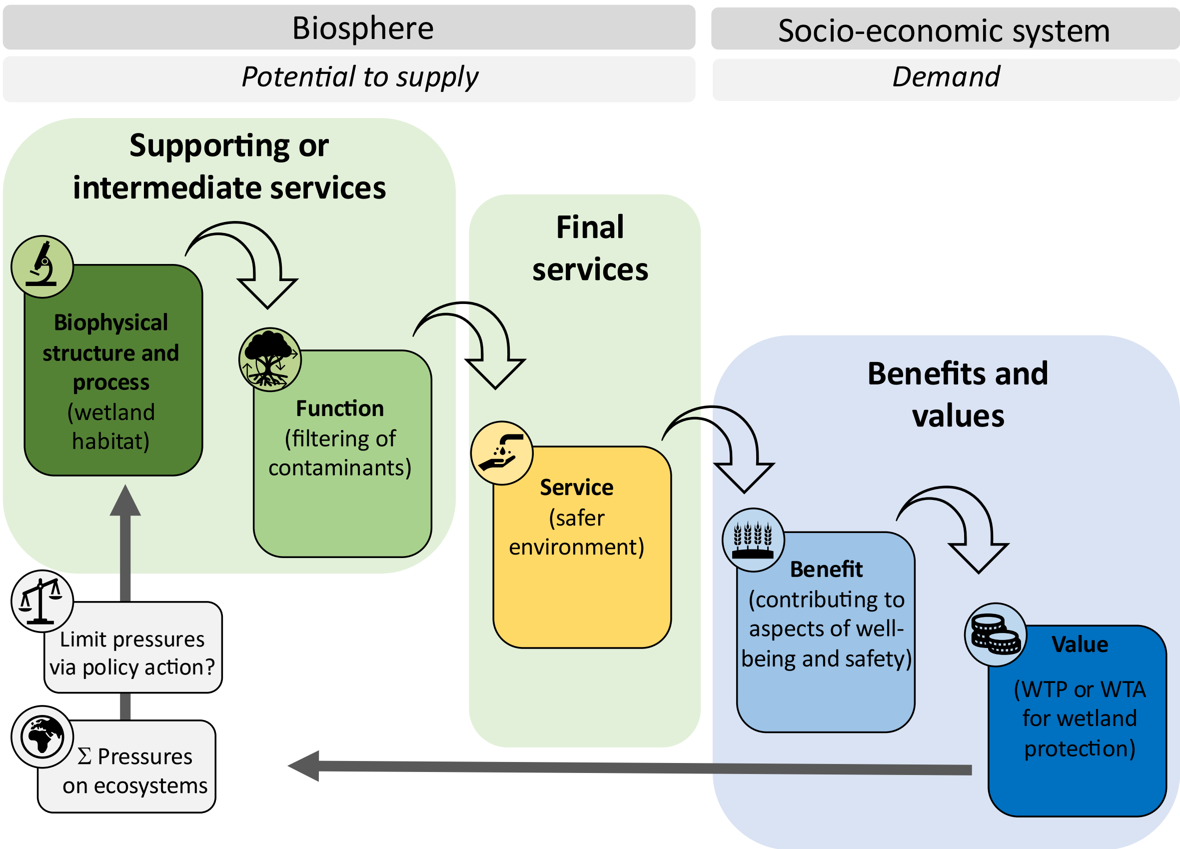


Figure 1: The Ecosystem Services Cascade (ESC) model for ecosystem services.
Note: Adapted from Haines-Young and Potschin (2010). The grey horisontal arrow represent pressure on ecosystems the develop as goods and benefits are used to enhance human welfare. First published in the licentiate thesis (Lundin Frisk, 2023).

2.3 Ecosystem Services in the Swedish Planning Process

The concept of ecosystem services has gained attention from both researchers and policymakers, with the expectation that it could drive essential policy reforms. However, its practical implementation has proven challenging, even in a favourable setting such as Sweden (Hysing, 2021; Sang et al., 2021). The ecosystem services concept was formally introduced in Sweden in the 2010, aligning with international and EU commitments, through its integration into Environmental Quality Objectives (EQOs)[4]

[4] The EQOs are a policy instrument in Sweden's environmental management. They define long-term targets for areas such as air and water quality, biodiversity, and climate impact, guiding policy and monitoring progress

that direct and guide Swedish environmental work (Hysing, 2021; Hysing & Lidskog, 2018). The EQOs were expanded eight years later, when additional targets were introduced and municipalities encouraged through this policy instrument to apply the ecosystem services concept in urban planning and administration, thereby reinforcing its practical implementation at the local level (Hysing, 2021; Sang et al., 2021). Despite these and other initiatives, author such as Hysing (2021) argue that assessments reveal that biodiversity and ecosystems in Sweden remain under threat, with critical policy instruments either absent or ineffectively applied. Communication efforts have raised awareness and fostered collaboration, still these efforts have not been sufficient to facilitate necessary shifts in societal attitudes, norms, and structures (Naturvårdsverket, 2018) and there is limited understanding of how ecosystem services can be operationalised as a tool in planning and decision-making (e.g. Beery et al., 2016; Schubert et al., 2018). The Swedish implementation has primarily focused on communication tools, such as guidance documents, rather than on legal or institutional integration (Hysing, 2021). This communicative emphasis is consistent with international research, which highlights the conceptual rather than instrumental use of ecosystem services (Saarikoski et al., 2018).

2.4 Ecosystem Services Indicators and Maps

Ecosystem service indicators are simplified measures used to assess the condition and trends of the biophysical environment and the services it provides to humans (Niemeijer & De Groot, 2008). Given the complexity of natural systems, indicators offer a practical means of monitoring environmental change, as it can be unfeasible to measure a given ecological variable. These indicators are widely employed in mapping and monitoring efforts, and extensive lists have been developed to cover a broad range of ecosystem services (see e.g. Grima et al., 2023). An illustrative example of such an indicator is the abundance of bees, used in for example Andersson-Sköld et al. (2018). The abundance of bees can serve as an indicator of pollination services, vital for the reproduction of many crops and wild plants. High bee populations typically signal strong pollination capacity, supporting both food production and biodiversity. Monitoring bee abundance thus provides insight into ecosystem health and the sustainability of agricultural systems reliant on natural pollinators.

Composite indicators, which integrate both the supply and demand of ecosystem services, are also commonly used (Layke et al., 2012). For instance, a water stress indicator may combine measurements or approximations of (i) water availability and (ii) water demand and describing their ratio to highlight areas of potential scarcity. These composite indicators could offer a more comprehensive understanding of where services are both available and needed, helping to identify mismatches that are critical for guiding conservation, restoration, and policy decisions. However, some researchers have advocated for separating indicators of service supply from those of demand and

towards sustainable development. More information is available at the Swedish Environmental Protection Agency webpage: https://www.naturvardsverket.se/om-miljoarbetet/sveriges-miljomal/

benefit to enhance their relevance in planning contexts that may require more flexibility (Andersson-Sköld et al., 2018).

Regardless of if a single or a composite indicator is used, for it to be effective, it must exhibit both high empirical accuracy and practical applicability. According to Potschin et al. (2016), indicators should be clear, understandable, sensitive to system changes, and capable of representing spatial and temporal aspects explicitly. Single-variable indicators, such as the abundance of bees or leaf cover, often fall short with regard to these criteria. Therefore, indicator sets, comprising both qualitative and quantitative elements, are frequently used to balance complexity with usability.

The creation of ecosystem service maps typically involves integrating ecological, biophysical, and socio-economic data using Geographic Information Systems (GIS). The process often begins with identifying the specific ecosystem services of interest, followed by collecting relevant information. Since it is often unfeasible (e.g. due to complex and costly sampling requirements) to measure a given ecological variable and connect it to a specific ecosystem service, it is common to use proxies and indicators (Maes et al., 2016). A practical example is mapping pollination services in agricultural regions. By combining data on wild bee habitats, crop types, and flowering periods, and using these as indicators for the pollination service, researchers can identify areas where pollination is strong and where it may be lacking, guiding conservation efforts like planting flower strips or preserving hedgerows. One of the more common proxies used is land cover data and ecosystem types (Maes et al., 2016). For example, the spatial distribution of wetlands are used as a proxy for typical wetland services such as stormwater regulation and water purification (Potschin et al., 2016). This land cover data is sometimes combined with other data sets or expert-based opinions to provide more detail and accuracy (Jacobs et al., 2015). The need for pragmatic tools to map ecosystem services has resulted in widespread applications of land-use-based proxy methods (van der Biest et al., 2015). The aim of such studies is often to identify areas that provide multiple ecosystem services, referred to as hotspots (Eigenbrod et al., 2010).

2.5 Valuation of Ecosystem Services

Economists estimate the value of ecosystem goods and services using various methods, developed and discussed in a substantial body of literature since the 1960s, largely depending on whether functioning markets exist. When markets are present, values can be directly derived from observable transactions, as is common for provisioning services like timber (Carpenter et al., 2006; Pascual et al., 2010). Deriving values from transactions on a market is known as direct market valuation, which include methods such as 1) market price-based approaches, 2) cost-based approaches, and 3) production function-based approaches. Market price methods rely on commodity prices to estimate service value, while cost-based approaches, such as Replacement Costs, Mitigative or Avertive Expenditures, and Damage Cost Avoided, infer value from the cost of replacing or avoiding service loss (de Groot et al., 2002). Production function approaches estimate how e.g. ecosystem services contribute to the production of goods that are traded in a well-functioning existing market (Pascual et al., 2010).

In the absence of such markets, values are instead inferred through hypothetical market construction, which often applies to cultural and regulating services. These are considered positive externalities and are typically valued by estimating individuals' willingness to pay (WTP) for preservation or enhancement, or willingness to accept (WTA) compensation for their loss or degradation. There are two main groups of methods that are used: revealed preference and stated preference methods.

Revealed preference methods infer value from observed behaviour in related markets, such as the Travel Cost Method (TC) that is commonly used for recreational services, based on the assumption that travel expenses and time reflect the price of access, and Hedonic Pricing (HP) that estimates how environmental attributes, such as air quality or proximity to green spaces, influence property prices. Stated preference methods on the other hand simulate markets through surveys. There are two main types of stated preference techniques, contingent valuation and choice modelling. Contingent Valuation (CV) directly asks respondents to state their WTP or WTA for a specific scenario. In contrast, Choice Modelling (CM) encompasses a broader set of stated preference methods, including Choice Experiments (CE), and involves presenting respondents with a series of hypothetical scenarios where they choose between different alternatives. These alternatives represent bundles of attributes, allowing for the estimation of trade-offs between them (Pascual et al., 2010).

When primary valuation is infeasible (e.g. due to budget constrains), value (or 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).

Regardless of the valuation method used, 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 the terminology can vary, these categories broadly correspond to direct use values, indirect use values, option values and non-use values (see Figure 2 for illustration). Direct use values arise from direct interaction with a resource, such as groundwater extraction or recreation, and mostly align with provisioning and cultural services (Pagiola et al., 2004). Indirect use values, such as flood regulation, provide benefits through their influence on other activities and correspond mostly to regulating services (Pagiola et al., 2004; Pascual et al., 2010). Whereas, option values reflect the potential for future use, either by the current or future generations, and span provisioning, regulating, and cultural services (Pagiola et al., 2004). Non-use values, such as existence or bequest values, are derived from the mere knowledge that a resource exists, even without intentions to use it (Pascual et al., 2010).

Together, these components (i.e. the use and non-use values) form the Total Economic Value (TEV), which captures all present and future benefits from natural capital in monetary terms (Figure 2). While monetisation facilitates comparison and decision-making, it is ethically debated, methodologically uncertain (Hausman et al., 2016; Spangenberg & Settele, 2016; Tinch et al., 2019), and potentially counterproductive for conservation goals (Gómez-Baggethun & Ruiz-Pérez, 2011). Nonetheless, valuation is often unavoidable, as it underpins everyday decisions and when conducted transparently, it can support more informed and accountable trade-offs (Freeman et al., 2014; Hanley & Barbier, 2009).

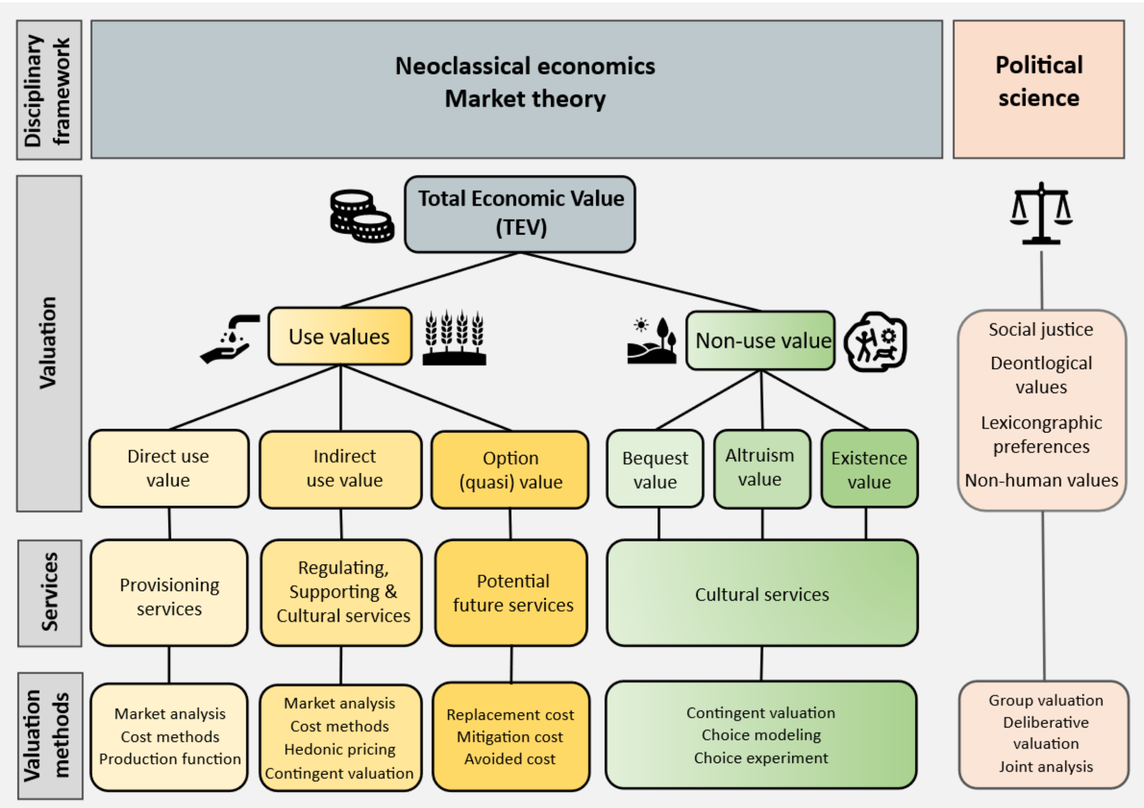


Figure 2: Generalised illustration of total economic value (TEV).
Note: Adapted from TEEB (2010a), modified according to Adhikari and Nadella (2011). First published in Lundin Frisk (2023).

2.6 Cost-Benefit Analysis

Cost-Benefit Analysis (CBA) is a decision-making tool, widely used for evaluating actions that involve trade-offs, particularly in contexts where interests may conflict. It has widespread application with respect to both countries and policy areas (Boardman et al., 2018). CBA systematically compares the positive (benefits) and negative (costs) impacts of an action on societal welfare, considering both present and future generations. The underlying principle is straightforward: if the total benefits of an action exceed its total costs to society, then implementing the action is expected to improve overall societal well-being and is therefore considered desirable. Actions assessed through CBA typically fall into two categories (Hanley & Barbier, 2009):

- Policy-oriented, such as the introduction or reform of government policies (e.g., implementing a new environmental tax; Pearce, 1998).

- Project-oriented, such as decisions on infrastructure investments (e.g., constructing a hydroelectric dam; Mishan & Quah, 2020).

To assess whether to carry out a given action, all relevant benefits and costs are identified, quantified, and expressed in a common unit, typically in a monetary unit, such as dollars, euros, or any other currency, as all relevant benefits and costs are required to be in in the same units to be aggregated (Boardman et al., 2018; Johansson & Kriström, 2016, 2018; Mishan & Quah, 2020). While market prices can provide this information for some services, they may be inadequate in cases of market failure or externalities. For instance, over-extraction of groundwater for irrigation may deplete nearby drinking wells, or the value of scenic landscapes may not be reflected in a market price. For these actions, market prices may no longer be a good guide to social costs and benefits (Mishan & Quah, 2020).

Once all monetizable costs and benefits are identified, they are converted into present values to account for the time value of money, recognising that people generally prefer benefits sooner and costs later. This is done using a discount rate, which reduces the weight of future costs and benefits relative to those occurring in the present (Hanley & Barbier, 2009). When all benefits and cost are monetised and discounted, the central decision rule in CBA is the Net Present Value (NPV) test[5]. 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. Mathematically, this is expressed as:

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad \text{Eq 1}$$

where B_t and C_t are the benefits and costs in year t, r is the social discount rate, and T is the time horizon of the project or policy.

Given that the benefits and costs in a CBA are discounted, it is important to note that there is no universally agreed-upon social discount rate for environmental CBA (see e.g. OMB, 2023; Trafikverket, 2024 for examples on different rates suggested) and that small changes in the chosen rate can dramatically alter the outcome of an analysis, making results highly sensitive and potentially contentious. Especially in the context of environmental impacts, that often unfold over decades or centuries, discount rates have been discussed as problematic (e.g. Dasgupta, 2008; Gollier, 2013; O'Mahony, 2021). One problem may arise is that high discount rates tend to undervalue long-term

[5] While NPV is the most commonly used criterion, alternatives such as the Internal Rate of Return (IRR) and the Benefit-Cost Ratio (BCR) are also employed. However, a detailed discussion of these alternatives is beyond the scope of this thesis (see e.g. Hanley & Barbier, 2009; Mishan & Quah, 2020 for further reading).

environmental benefits, potentially justifying actions that harm future generations for short-term gains (Dasgupta, 2008; O'Mahony, 2021).

Ultimately, CBA addresses a fundamental economic challenge: how to allocate scarce resources in the face of unlimited demands. Regardless of its limitations, it offers a transparent and systematic framework for evaluating the economic impacts of policies and projects over time. Moreover, through distributional analysis of the benefits and costs, CBA can help identify which stakeholders benefit and which bear the costs of a given action. That said, it is important to note that a CBA is grounded in a consequentialist ethical framework, meaning that decisions are evaluated based on aggregate outcomes rather than duties or intrinsic values (Boardman et al., 2018; Johansson & Kriström, 2016, 2018; Mishan & Quah, 2020). Consequently, a CBA does not account for deontological considerations such as the intrinsic worth of the environment or social justice principles that cannot, or are difficult to, monetise.

2.7 Subsurface Planning

The global urban population increased dramatically, from just 7% in the 1800s to 16% by the 1900s, this rapid urbanisation led to dense and often disorganised spatial expansion, accompanied by a range of social and environmental challenges (Volchko et al., 2020). In response, as outlined in Volchko et al. (2020), most European countries established spatial planning systems during the 20th century to guide urban development, often under strong state control. Despite these advances, a review of spatial planning practices across Europe reveals that the systematic inclusion of the subsurface in city-scale planning remains largely absent (Mielby et al., 2017; Öberg & Sjöholm, 2019).

In many cases, subsurface use is governed by a first come, 'first served' principle, which can lead to uncoordinated and conflicting developments below ground (van der Meulen et al., 2016b; Volchko et al., 2020). There are, however, notable exceptions, one of the more advanced examples is the Underground Master Plan of Helsinki, Finland, a pioneering initiative that strategically manages the use of subsurface space for future underground construction (Vähäaho, 2014; Volchko et al., 2020). This legally, binding plan, reserves underground areas for both public and private utilities, including infrastructure tunnels, and provides a framework for coordinating and regulating underground construction (Vähäaho, 2014). A similar initiative is currently underway in Singapore, where an Underground Master Plan is being developed to manage the city-state's limited surface space and growing infrastructure needs (Yan et al., 2021).

In contrast, subsurface planning in many other countries remains sectoral and fragmented and separate plans are often developed for specific uses such as mining, mass transit, energy and water infrastructure, sewage systems, and telecommunications (Craig-Thompson & Kuchler, 2025; Volchko et al., 2020). This is highlighted in the examples brought up in Volchko et al. (2020) of such sectoral approaches can that be found in cities like Montreal and Toronto (Canada), and Brisbane (Australia) (Delmastro et al., 2016), as well as in Tokyo, Osaka, and Nagoya (Japan) (Kishii, 2016). In Sweden and Norway, underground planning is similarly handled through sector-specific processes (Broch, 2016; Tengborg & Sturk, 2016). This show that, subsurface planning is interpreted and applied differently across contexts.

In the context of this thesis, the term refers to the systematic planning and management of the underground, with the aim of ensuring coordinated, sustainable, and efficient use of subsurface resources. One way to conceptualise subsurface planning is to divide it into two main components: 1) prioritisation of subsurface uses, which involves managing competing interests and resolving potential conflicts between different functions; and 2) integration of surface and subsurface use, which addresses how above-ground development can be designed to make optimal use of subsurface resources (see e.g. Norrman et al., 2020).

Chapter 3
METHOD

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

This thesis adopts a mixed-methods research design to review the concept of geosystem services and to investigate how it may contribute to improved subsurface planning. The research is structured around three peer-reviewed articles and one manuscript, each contributing distinct methodological perspectives and/or empirical insights. A schematic overview of the research process with methods used and how the results feed into achieving the research aim is presented in Figure 3.

While each article employs distinct methods, they are unified by a shared focus on operationalising the geosystem services concept for planning practice. The conceptual review of geosystem services in **Publication I** underpins the subsequent articles, **Publications II-IV**, that address different aspects of the concept, moving from a more theoretical perspective to a more applied standpoint in later publications. This sequential integration allows for a cumulative understanding of both the technical and societal dimensions of geosystem service in planning processes.

3.1 Literature Reviews

Multiple literature reviews contributed to fulfilling the overall aim and the specific objectives of this thesis through thematic exploration. A modified variant (see **Publication I-III** for details on modification) of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009) was followed for the systematic literature reviews, which were carried out to:

1) identify articles in which a definition of geosystem services was given, or could be inferred from (**Publication I**),

2) to identify peer-reviewed articles using mainstream environmental economics to, in monetary terms, value changes in the provision of non-market geosystem services and ecosystem services caused by changes in abiotic structures and processes of the subsurface (**Publication II**),

3) to synthesise a list of indicators for geosystem services related to the subsurface (**Publication III**).

The PRISMA protocol was slightly modified in **Publications I-III** as certain steps were not applicable (e.g., sensitivity analyses and certainty assessments). Additionally, the

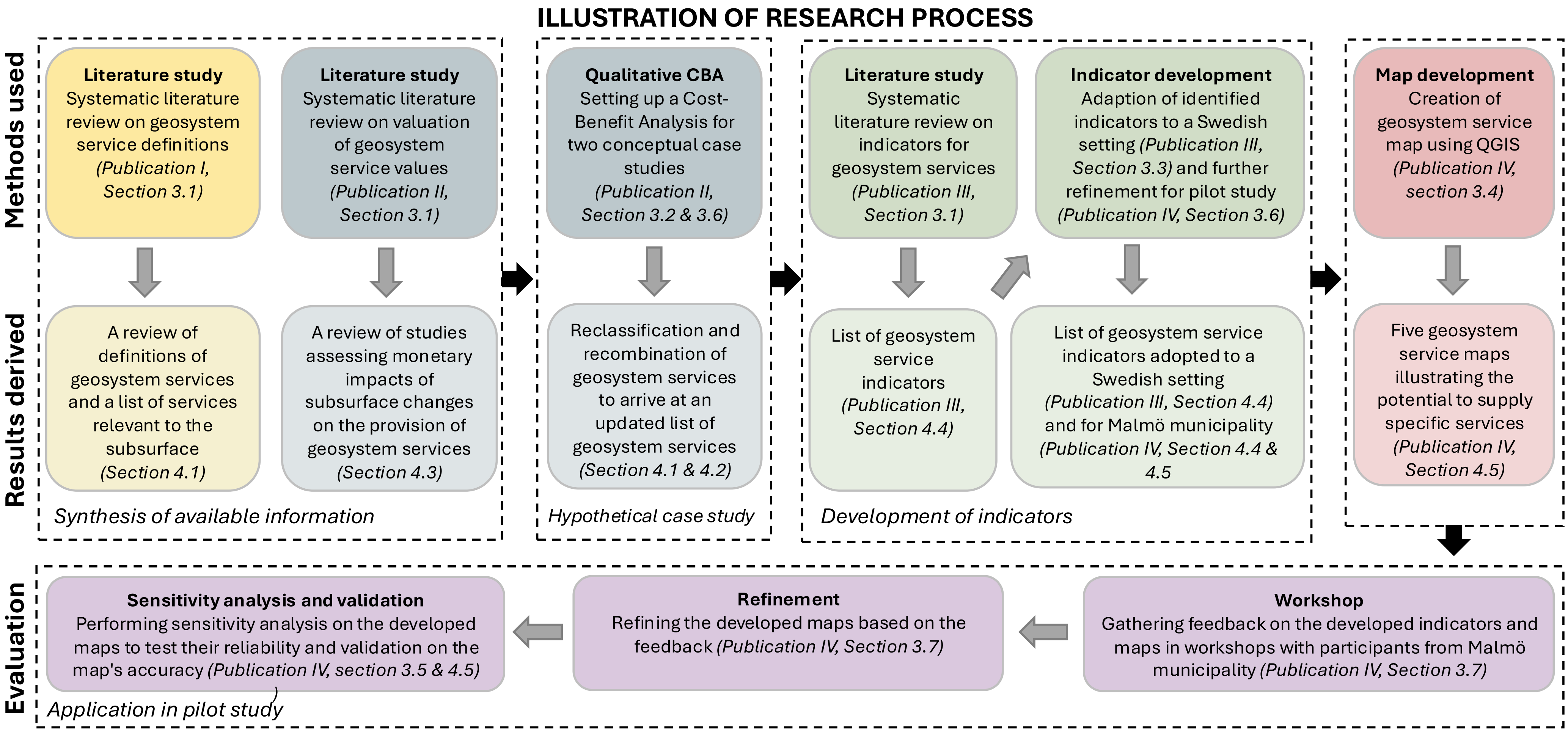


Figure 3: Schematic overview of the research process, methods used and progress towards achieving the overall aim of the thesis.

study selection and data extraction were conducted by a single researcher rather than two independent researchers. The search involved identifying keywords and using the Scopus database to retrieve relevant documents (Figure 4). The titles, abstracts, and keywords of these documents were initially screened, and irrelevant documents were removed. The remaining documents were read in full to assess their eligibility. Documents that did not meet the search criteria were subsequently excluded (see each Publication for search criteria and keywords used). Documents deemed relevant to the research aim were synthesised and included in the specific study. Figure 4 gives an overview of the PRISMA process and the number of documents found in the different searches. For detailed description of the search criteria used and the number of documents retrieved, see each individual publication.

The systematic review in **Publication III** was complemented by a review of indicators found in technical reports (so-called grey literature). These technical reports included reports written by governmental agencies, municipalities, and consultants. The search was broadened to fill gaps (i.e. if no indicator is found for a specific service) left by the systematic review and/or to adapt indicators to the specific study setting (e.g. adaptation to specific lithological units). However, as there is no (global) searchable database for these types of sources, only general searches in the Swedish (https://www.sgu.se/en), Finnish (https://www.gtk.fi/en) and Norwegian (https://www.ngu.no/en) geological surveys' website databases were conducted, in conjunction with backward and forward reference searches of identified key reports. This search resulted in an additional 21 reports that contained descriptions of geophysical structures and processes that were relevant to research aims of **Publication III**.

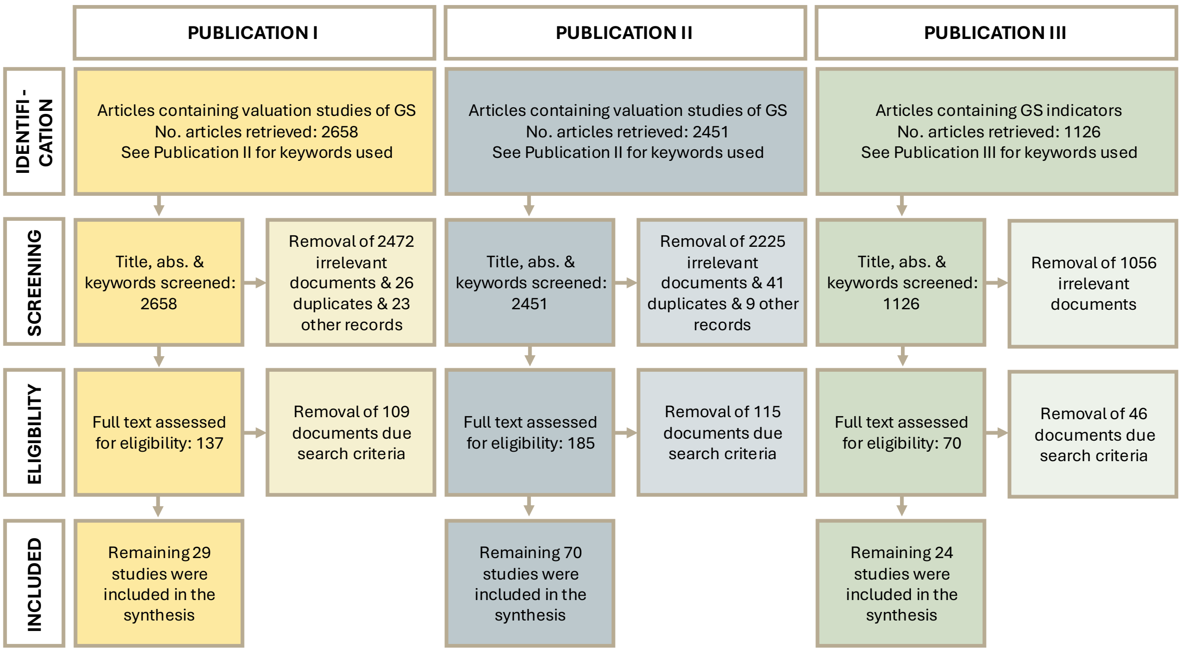


*Figure 4: Schematic overview of systematic literature searches in carried out in **Publication I-III**.*
***Note**: See each individual Publication for keywords used, inclusion and exclusion criteria as well as the time periods the search was conducted.*

3.2 Cost-Benefit-Analysis of Underground Projects

Application of geosystem services in underground planning context emphasises the importance of understanding the complex geophysical system and its coupled processes (thermal, hydraulic, mechanical, chemical, and biological) to be able describe the impacts of subsurface projects. In **Publication II** this is illustrated by two conceptual cases: the construction of a tunnel through fractured crystalline rock and the exploitation of a glaciofluvial delta deposit for geomaterial extraction. The impacts on geosystem services from these projects are qualitatively described and translated into a qualitative CBA to highlight the trade-offs and complexities that arise from these types of projects at the societal level. Following standard CBA theory (Johansson & Kriström, 2016, 2018), a generalised equation to derive a net present value (NPV) of a project affecting market-priced services is presented in **Publication II**.

To incorporate the value of non-market services (S), i.e., those that are not subject to trade at any market and therefore lack market prices, is economically valued through the associated willingness to pay (WTP) or willingness to accept compensation (WTA), i.e. monetary measures of consumer surplus (Freeman et al., 2014). To also consider this impact, the standard equation to derive a NPV was extended to include changes in the availability of non-market services (see details in **Publication II**). This includes both geosystem and ecosystem services affected by the subsurface project.

3.3 Geosystem Services Indicators

Mapping geosystem services required the development of appropriate indicators, which was carried out through a three-stage process. First, a synthesis of geophysical indicators from existing literature was conducted (see Section 3.1 or **Publication III**). Second, the identified indicators were screened for their relevance to subsurface geosystem service potential and their applicability in a Swedish context. This selection was informed by internal project discussions and input from an external expert. Third, the selected indicators were categorised into capacity class system, ranging from Class D (no or limited capacity; numeric value 0) to Class A (highest capacity; numeric value 3). Intermediate levels are defined as Class C (some capacity; value 1) and Class B (moderate capacity; value 2). The scale is ordinal and based on expert judgement or literature. It is thus, relative to the study area and not an absolute measure of capacity (Table 1). The classification approach follows the methodology of Andersson-Sköld et al. (2018) for assessing urban greenery benefits, and is conceptually similar to point-based systems used for geological and geomorphological features, in other frameworks (e.g. Bathrellos et al., 2012; Depountis, 2023).

To illustrate capacity classes in a tangible manner: different geological materials (geomaterials) exhibit varying infiltration capacities, which are grouped into capacity classes. For instance, in the context of stormwater infiltration: sands, with their coarse and well-sorted assembly of particles, typically allow rapid water infiltration both in the horizontal and vertical directions, whereas clays, due to their fine particles and compact structure, have much lower infiltration rates.

Nevertheless, both materials can contribute to infiltration under suitable conditions, but to different degrees. This variability is captured through capacity classification.

3.4 Maps of Geosystem Services Potential

The geosystem services maps establish a link between the geophysical environment and the potential to deliver specific geosystem services, using the developed set of indicators (see **Publication III & IV** for details on the indicators) that link specific geophysical settings with the potential to supply a given service. The mapping process followed five main steps that are described in detail in **Publication IV**, illustrated in Figure 5, and is outlined below.

1. A cartographic grid was superimposed on the municipality. Each cell measured 10×10 metres (except for the service of underground space, see **Publication IV**).

2. Each cell was assigned a value from 0 (No or limited potential) to 3 (Highest capacity) based on the geophysical environment and its associated capacity classification. The potential supply of a geosystem service in a given cell is conceptualised as the combination of

    a. the presence and spatial extent of a specific geophysical environment, and

    b. the inherent capacity of that environment to contribute to service delivery.

    Thus, to estimate the potential supply of a specific geosystem service within a given cell, the geophysical environment that occupies the largest proportion of this cell is first identified. Among the parameters that constitute the indicator for that environment, the minimum value is then selected to represent the overall potential supply of the geosystem service in that cell. This ensures that the parameter with the lowest capacity acts as the limiting factor in the assessment. To illustrate; in the case of infiltration as in the previous example, soil texture alone is insufficient to alone indicate the potential. Other factors, such as soil depth and groundwater level, also govern infiltration potential. Shallow soils may lack sufficient volume for water retention, and high groundwater levels can saturate the soil, eliminating the unsaturated zone necessary for infiltration. Consequently, some of the indicators used to indicate potential integrate multiple aspects that collectively reflect the environment's ability to support a given service, i.e. a single indicator can consist of several independent parameters. See **Publication IV** for details on of the potential supply of a geosystem service in a given cell is expressed mathematically.

3. To estimate the effective potential, i.e., the supply that is both available and suitable for use, each cell's potential was adjusted based on suitability and accessibility considerations. To exemplify; a given environment (e.g. glaciofluvial deposit with coarse sand) may have an inherently good potential to infiltrate stormwater. However, this potential may be locked out from utilisation by an

impermeable surface such as asphalt (accessibility) or by a lack of willingness to utilise the potential due to contamination concerns (suitability).

Accordingly, the effective potential to supply a specific geosystem service, i.e. the potential that is actually available for utilisation, is the minimum value of the potential, and the suitability and accessibility classification (Table 1). The suitability and accessibility grading were determined after internal discussions among the authors, taking into account a) knowledge of common accessibility and suitability concerns and b) existing literature (for details see **Publication IV**).

4. The geosystem service potential, G(i), and effective potential, E(i), were aggregated into thematic maps (TMs) by summing relevant service indicators within each theme. For each service, two maps were produced: one showing the potential supply and another incorporating suitability and accessibility constraints.

Table 1: List of capacity, accessibility and suitability classes.

Class	Label		Description
Capacity to supply a given geosystem service indicated by a given indicator	A (3)	Highest capacity	High contribution to the supply of the given geosystem service
	B (2)	Moderate capacity	Moderate contribution to the supply of the given geosystem service
	C (1)	Some capacity	Some contribution to the supply of the given geosystem service
	D (0)	No or limited capacity	Limited contribution to the supply of the given geosystem service
Accessibility	N/A	No restrictions in terms of accessibility	Does not present meaningful restrictions to the provision of the service
	C (1)	Limited accessibility	Imposes some limitations on the provision of the service, but not to a prohibitive extent
	D (0)	Inaccessible	Significant constraints that preclude the provision of the geosystem service
Suitability	N/A	No restrictions in terms of suitability	Does not present meaningful restrictions to the provision of the service
	C (1)	Conditionally suitable	Imposes some limitations on the provision of the service, but not to a prohibitive extent
	D (0)	Unsuitable	Significant constraints that preclude the provision of the geosystem service

Note: The scale is ordinal and based on expert judgment or literature. It is relative to the study area and not an absolute measure of capacity.

Figure 5 illustrates the map creation process for the geosystem service 'regulation of water quantity', specifically the service of 'infiltration of stormwater'. The figure serves as an example of the methodological steps involved in producing these maps, and demonstrates how information was compiled, processed, and visualised to represent service potential together with accessibility and suitability constraints.

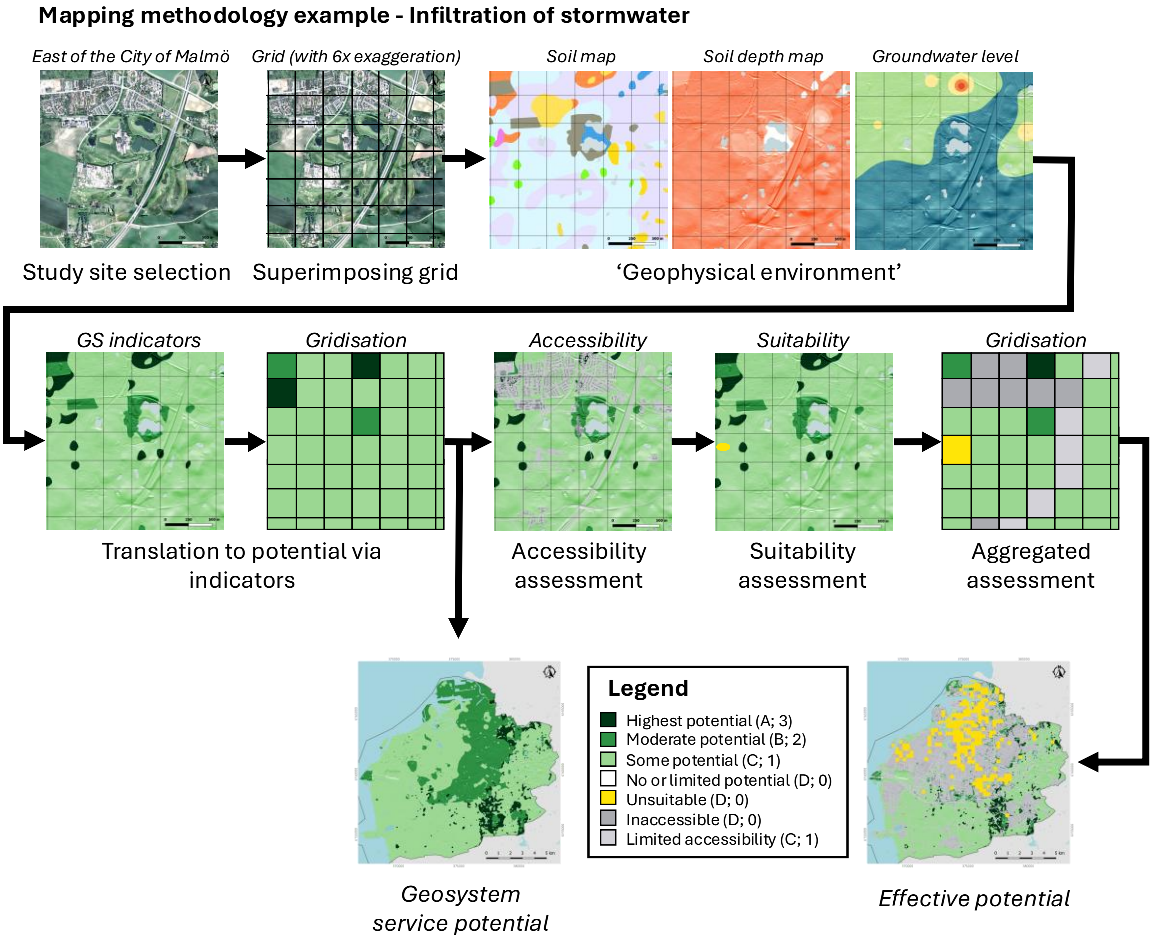


Figure 5: Methodological illustration geosystem service mapping.
Note: The maps shown in the illustration relates to the service: 'Regulation of water'. The specific use is to infiltrate stormwater and thereby delay water discharge to adjacent streams.

3.5 Sensitivity Analysis and Validation of Maps

To evaluate how variations in assumptions related to the capacity classes (i.e., different scenarios) affect the resulting maps (see **Publication IV** for scenarios tested), a sensitivity analysis was conducted. This was performed in QGIS by systematically adjusting input parameters and comparing alternative scenarios, to highlight how changes in assumptions, such as treating filling materials as having low rather than high infiltration capacity, affect the resulting maps.

In each scenario, capacity class values were shifted one to two levels up or down from their original values, following a one-factor-at-a-time (OFAT) design. This allows for identification of the parameters exerting the greatest influence on the final maps. Two complementary metrics were applied in the sensitivity analysis: Range-based Normalised Average Root Mean Square Error (NA-RMSE) and the Map Disagreement Index (MDI).

The Root Mean Square Error (RMSE) measures the average magnitude of differences between a scenario map and a reference map, where values near 0 indicate scenarios closely match the basemap (reference). To make this measure comparable across datasets and scales, RMSE was normalised by the max and min values of the reference raster. See **Publication IV** for details and how the RMSE is expressed mathematically.

While NA-RMSE focuses on deviations from a single reference, the second metric, MDI summarises internal consistency among all maps. It is based on the Average Pairwise RMSE (AP-RMSE) across all unordered pairs of maps (including the reference), which is then normalised by the global range of values across all maps. The MDI quantifies the overall disagreement among maps on a 0–1 scale, indicating whether uncertainty is concentrated in a few scenarios or widespread. An MDI close to 0 suggests that maps are nearly identical, whereas an MDI close to 1 indicates differences as large as the entire value range. However, it does not reflect deviations from actual geosystem service provision (see e.g. Schulp et al., 2014). To address this, the maps were also compared with independent datasets serving as proxies for geosystem service supply (see Table 1 in **Publication IV**). Spatial overlap between high-potential areas and these proxies is interpreted as an indicator of model quality.

3.6 Application and Demonstration (Case and Pilot Studies)

Geosystem services as a concept, and the methods that have been developed as part of **Publications II-IV**, have been applied and demonstrated in case and pilot studies as part of an iterative development cycle. In this cycle, feedback from the applications and demonstrations is used to further elaborate the theory behind geosystem services as a concept (e.g. reclassifications of services as suggested in **Publication II**). Which in turn is used when developing methods (e.g. development of indicators, **Publication III** and geosystem service maps, **Publication IV**). See Figure 6 for an illustration of this cycle. To exemplify, the information used to set up the qualitative CBA in **Publication II** was employed to refine and reconceptualise certain geosystem services, resulting in an updated list of services considered in subsequent work.

The case studies represent different contexts and spatial scales, ranging from project to national scope. In **Publication II**, two hypothetical case studies representing typical geological settings and underground activities found in Scandinavia were set up to assess how different subsurface projects might affect the supply of geosystem services and to develop a framework for systematically incorporating these impacts. Case 1 involves the construction of a tunnel through fractured crystalline bedrock,

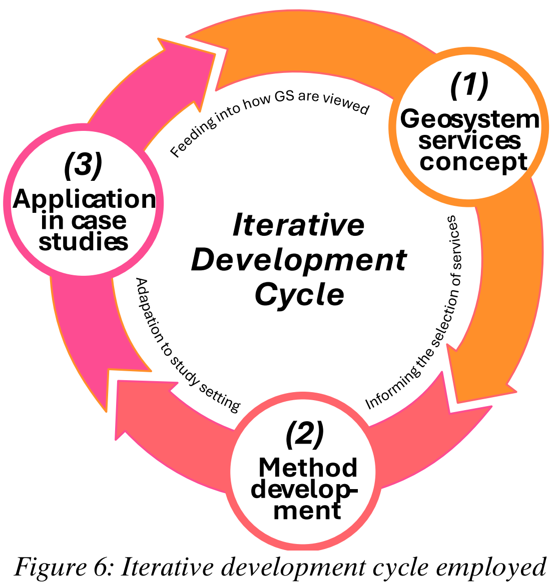


Figure 6: Iterative development cycle employed in the thesis work.

while Case 2 considers the extraction of geomaterials from a glaciofluvial delta deposit (Figure 7).

In **Publication III**, the developed geosystem services indicators are adapted to a national scale, with a specific focus on Sweden. These indicators are tailored to align with the country's climatic and geological conditions, while also accounting for the availability of relevant data. Geologically, Sweden is part of the Fennoscandian Shield, a tectonically stable region within the East European Craton. It is characterised by a relatively young overburden, shaped by multiple cycles of glaciation and deglaciation during the Quaternary period (Stephens, 2020; Wastenson & Fredén, 2002). The availability of general geological data is relatively high, with national agencies such as the Geological Survey of Sweden maintaining extensive, publicly accessible records.

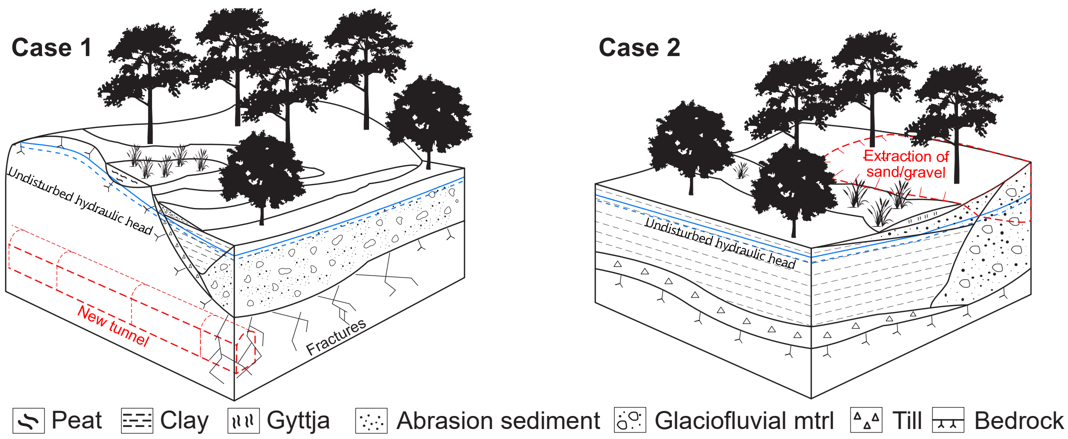


Figure 7: Illustration and schematic cross-sections of the two conceptual cases.
***Note:** Case 1 refers to the construction of a new tunnel through fractured crystalline bedrock. Case 2 refers to the extraction of geomaterials from a glaciofluvial delta deposit. The subsurface projects are marked in red. The undisturbed hydraulic head is marked with blue.*

Finally, in **Publication IV**, the indicators from **Publication III** were applied and adapted for use at the municipal scale in Malmö to create geosystem service maps. Located in southwestern Sweden, Malmö is the country's third-largest city and is actively developing a climate resilience plan to address challenges such as sea-level rise, stormwater infiltration, heatwaves, and drought. Climate projections (based on climate change modelling) for Scania suggest that heavy rainfall events may become 8–10 times more frequent, with intensities increasing by 20–30%. Under RCP 8.5, the number of days exceeding 25°C is expected to rise from 10.5 to 49 annually by century's end (Sonesson et al., 2024), alongside longer and more frequent droughts (Persson et al., 2012). Similar trends are projected under a RCP 4.5, though to a lesser extent. Some of the geosystem services might mitigate some of these impacts, possibly making the mapping of their potential supply valuable for climate resilience planning. Please refer to **Publication IV** for a detailed description of the Malmö setting and the climate challenges it faces. The region is not part of the Fennoscandian Shield and therefore differs somewhat, in broad geological terms, from the generalised descriptions used in **Publication II** and **III**.

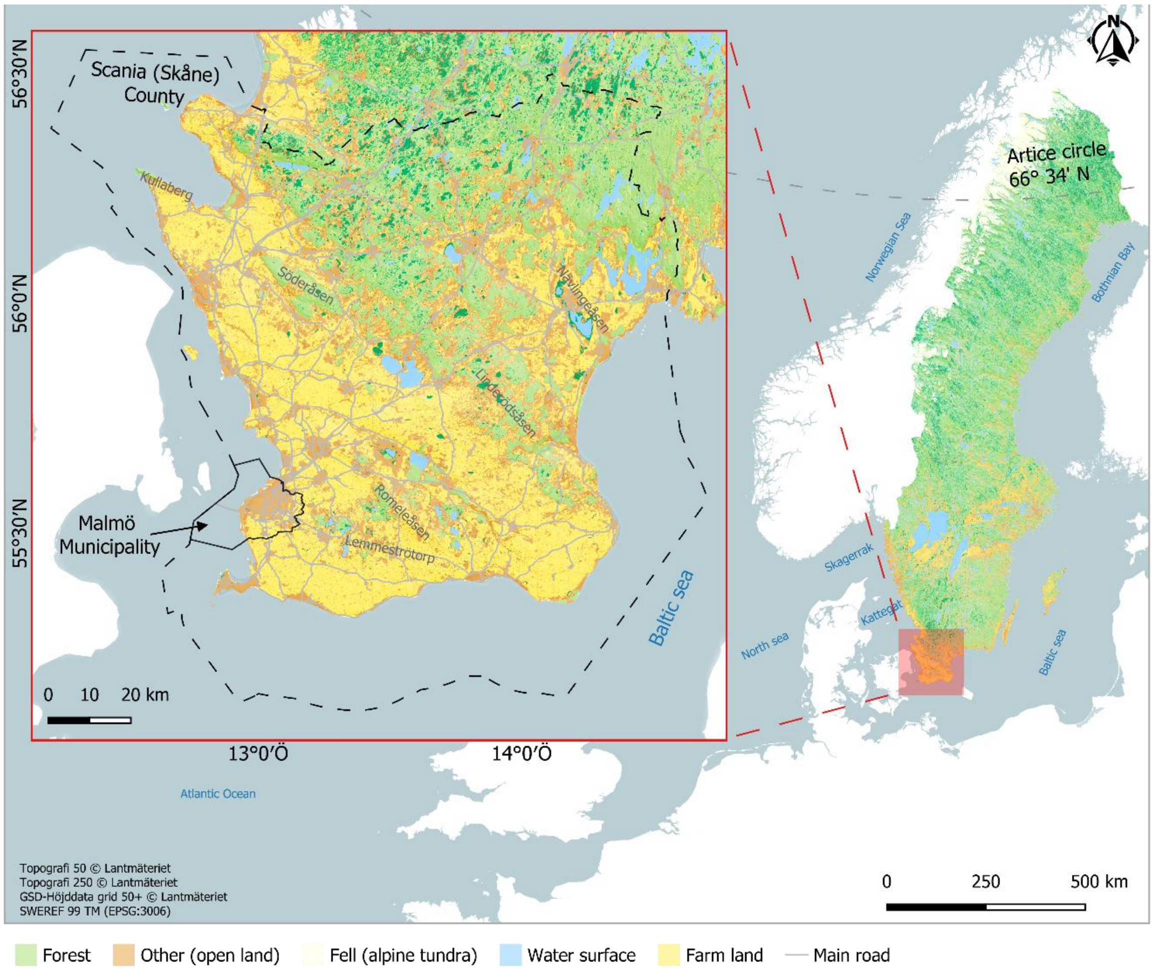


*Figure 8: Overview map of Scania (Skåne) and the study area (Malmö municipality) for the pilot study in **Publication IV**.*

3.7 Workshop

To evaluate the geosystem service maps developed in **Publication IV**, a workshop was held together with the City of Malmö. Seven civil servants participated, all involved in urban planning, climate resilience, or sustainability, representing potential end users of the developed maps. After a brief introduction, participants were divided into smaller groups to discuss the maps' usability and added value in comprehensive planning. Their feedback was used both to refine the maps and to assess how planners perceived the usability of the maps. See **Publication IV** for a detailed description of the workshop set-up.

Chapter 4
RESULTS & DISCUSSION

This chapter summarises the main results and discussion of the appended papers. It begins with a review of current definitions of geosystem services and an outline of the services derived from the subsurface.

4.1 Geosystem Services – Definitions and Identified Services

Focusing on geosystem services as an independent concept, current definitions and categorisations of geosystem services (GS) were reviewed in **Publication I.** This review identified two prominent, yet distinct interpretations of geosystem services:

A. Geosystem services as underpinned by geodiversity, which includes the natural range of geological, geomorphological, (top)soil, and hydrological features (Gray, 2013).

B. Geosystem services as related to services from the subsurface, which includes goods and services that contribute to human well-being specifically resulting from the subsurface (van Ree et al., 2017).

These two definitions not only differ spatially (i.e., surface versus underground) but also reflect different approaches to the interactions between abiotic and biotic components (see Figure 9 and Figure 10 for graphical illustrations of the two definitions).

The difference between the two definitions can be illustrated through the different usage of geosystem services by Gray (2013, 2018), representing definition A, and van Ree and van Beukering (2016) representing definition B. Gray (2013, 2018) referred to geosystem services as the wide range of abiotic services that are the direct result of the planet's geodiversity. Hence, in this context, geosystem services constitute only the abiotic parts of the environment, but without differentiation between suprasurface, surface and subsurface features. In contrast, van Ree and van Beukering (2016) used the term geosystem services to refer to services specifically derived from the subsurface. While the subsurface is generally associated with low biological activity due to the lack of sunlight and often anaerobic conditions, it still hosts microorganisms that are beneficial to human society and are thus included in van Ree's definition of geosystem services.

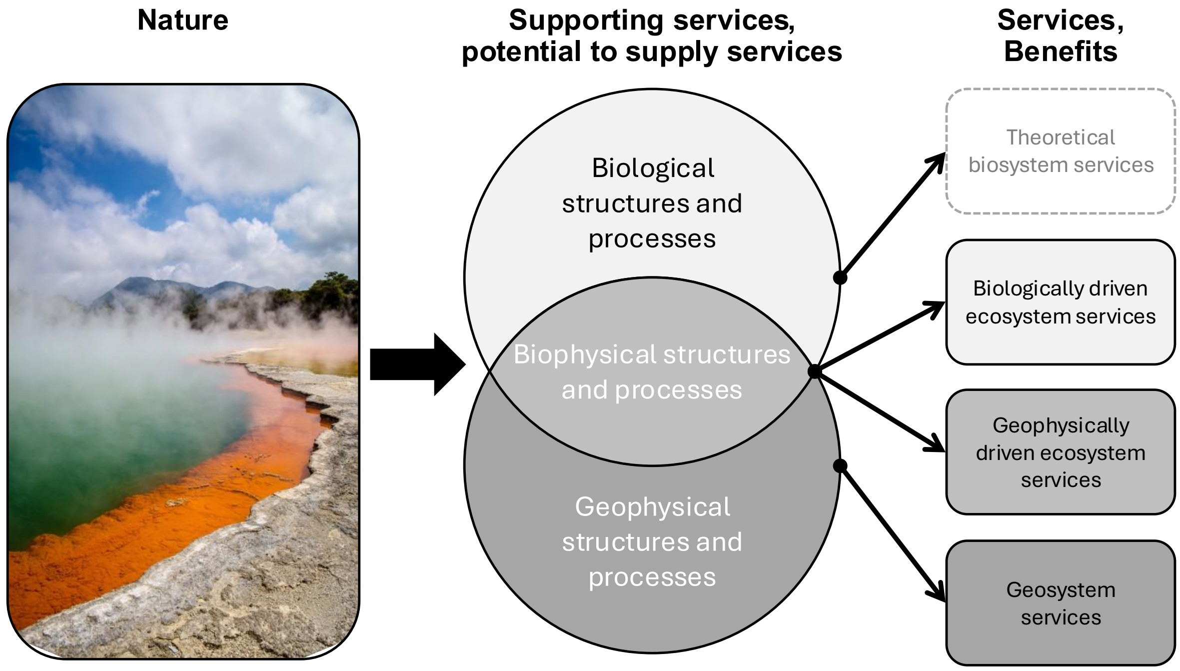


Figure 9: Illustration of definition A.
Note: Adapted after Fox et al. (2020). Geosystem services as underpinned by geodiversity, which includes the natural range of geological, geomorphological, soil, and hydrological features (Gray, 2013).

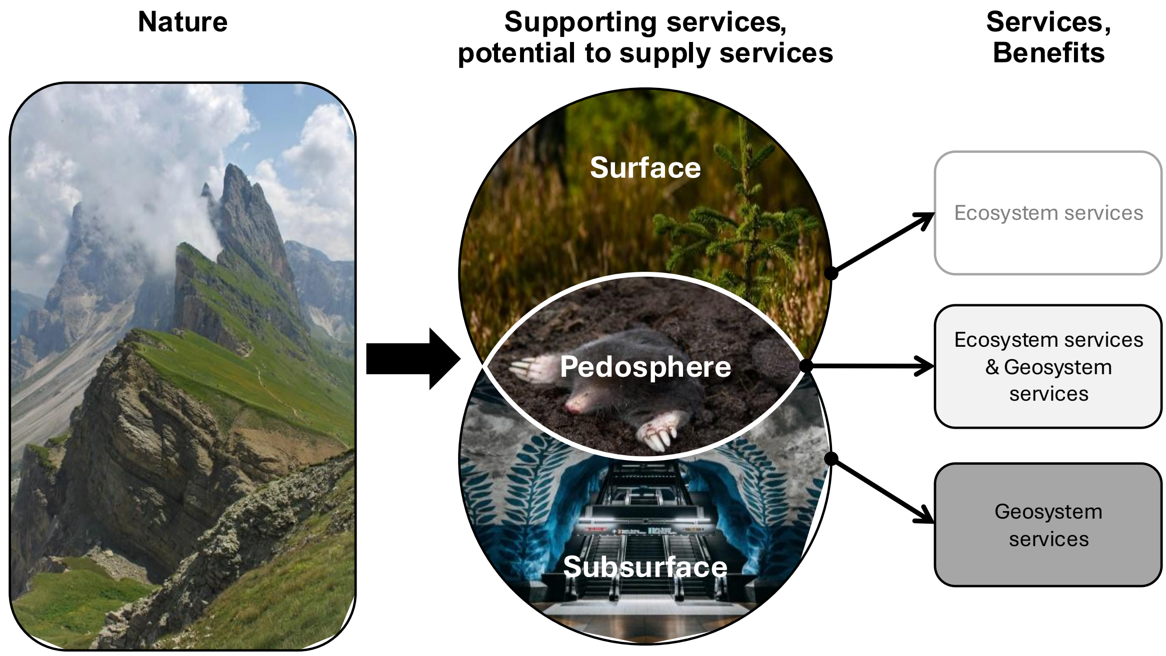


Figure 10: Illustration of definition B.
Note: Geosystem services as related to services from the subsurface, which includes goods and services that contribute to human well-being specifically resulting from the subsurface (van Ree et al., 2017).

Based on the literature review on geosystem services (see **Publication I** for details), a list of the services mentioned in the literature (i.e. list of services that have been labelled as geosystem services) was synthesised (see Figure 11 graphical illustration of said services). This gross list of services was compared to the widely adopted Common International Classification of Ecosystem Services (CICES) V5.1 framework and its abiotic extension (in the more recent V5.2, these services have been relabelled as geophysical services in the framework) to highlight services that already considered in

Figure 11: Illustration of geosystem services identified in the literature review in Publication I.
Note: Services marked with **X** were assessed as not relevant for subsurface planning. It is also noted if the service is already included in the CICES framework.

Continuation of Figure 11.

ecosystem service frameworks. Of the 39 geosystem services listed in the reviewed literature, 31 are already included in the abiotic extension (Haines-Young & Potschin-Young, 2018), with additional services incorporated in the newly revised version V5.2 (Haines-Young, 2023).

Nevertheless, as illustrated in Figure 11 some essential services are still omitted. The omitted services primarily pertain to supporting services such as 'Retention of water in soils', 'Soil development', 'Retention of nutrients in soils', 'Habitat provision', 'Stable platform to build on and within', 'Underground space', and 'Disposal and storage'. Supporting services, referred to as intermittent services in some publications, are contentious within ecosystem services frameworks such as CICES, as they may present a risk of double-counting when they function as inputs to other ecosystem services (Jax, 2016; Potschin & Haines-Young, 2016). That said, van Ree and van Beukering (2016) and van der Meulen et al. (2016a) have argued that some of the supporting geosystem services should be viewed as final services as they relate to carrier functions of the geological substrate, which can be directly utilised by humans to provide services related to well-being (e.g., extracting physical underground space or utilising the underground's ability to store and transmit heat in shallow geoenergy systems).

4.2 Assessments of Effects on the Subsurface

From the list of geosystem services (Figure 11), 25 services were considered relevant to include in a subsurface planning context. This revised set of geosystem services relating to the subsurface (see Figure 13 or an illustration of some examples) can serve, for instance, as a checklist to systematically assess the contributions of subsurface services and ensure that important aspects are not overlooked. That said, the subsurface (and nature more broadly) is more complex and interconnected than this list suggest. Understanding the impacts of an underground project requires a solid grasp of this intricate system, as the processes, thermal, hydraulic, mechanical, chemical, and biological, are typically coupled. In other words, a change in one location may trigger effects elsewhere, which can be both beneficial and detrimental. To illustrate; a reduction in the infiltration capacity of the subsurface at one site may lead to increased surface runoff, resulting in higher downstream flows during heavy rainfall events, resulting in flooding at another location.

One way to systematically gain an overview of the potential effects of a given subsurface project is through a framework based on geosystem services, as illustrated in **Publication II**. This framework was exemplified using two hypothetical projects. For each listed geosystem service, the effects of the conceptual projects are qualitatively assessed from a process-oriented perspective, considering impacts on and interactions between thermal, hydraulic, mechanical, chemical, and, to some extent, biological processes. The impacts are categorised qualitatively as negative (−), positive (+), mixed or uncertain (+/−), or no effect (0). The mixed category (+/−) is included to acknowledge that certain aspects may lead to both beneficial and adverse outcomes.

These effects can also be translated into a cost–benefit analysis (CBA) context as qualitative cost and benefit items. Building upon the two hypothetical cases in **Publication II**, both were translated into a CBA context to illustrate such a procedure. This translation highlights that some geosystem services, much like ecosystem services, may function as intermediate services in the production of final services. To exemplify, both case studies in **Publication II** indicate a reduced capacity to regulate groundwater quantity and quality (costs C6 and C7 in Table 3 in **Publication II**). This, in turn, is likely to lead to decreased access to groundwater for extraction (cost C12, *ibid.*) and negatively affect services provided by groundwater-dependent ecosystems (cost C15, *ibid.*). Monetised estimates of reduced groundwater access and ecosystem service degradation are therefore likely to implicitly include the diminished regulatory capacity of the subsurface. The analysis also underscores that some potentially negative impacts on geosystem services may be fully or partially mitigated through measures whose costs are already accounted for in investment or operation and maintenance budgets (cost C1, *ibid.*). For example, this is assumed to be fully the case for the reduced capacity to regulate erosion and mass movements (cost C5, *ibid.*), as the project owner is expected to stabilise the construction site. In contrast, this assumption applies only partially, or not at all, to other geosystem services, where mitigation measures are either limited or absent.

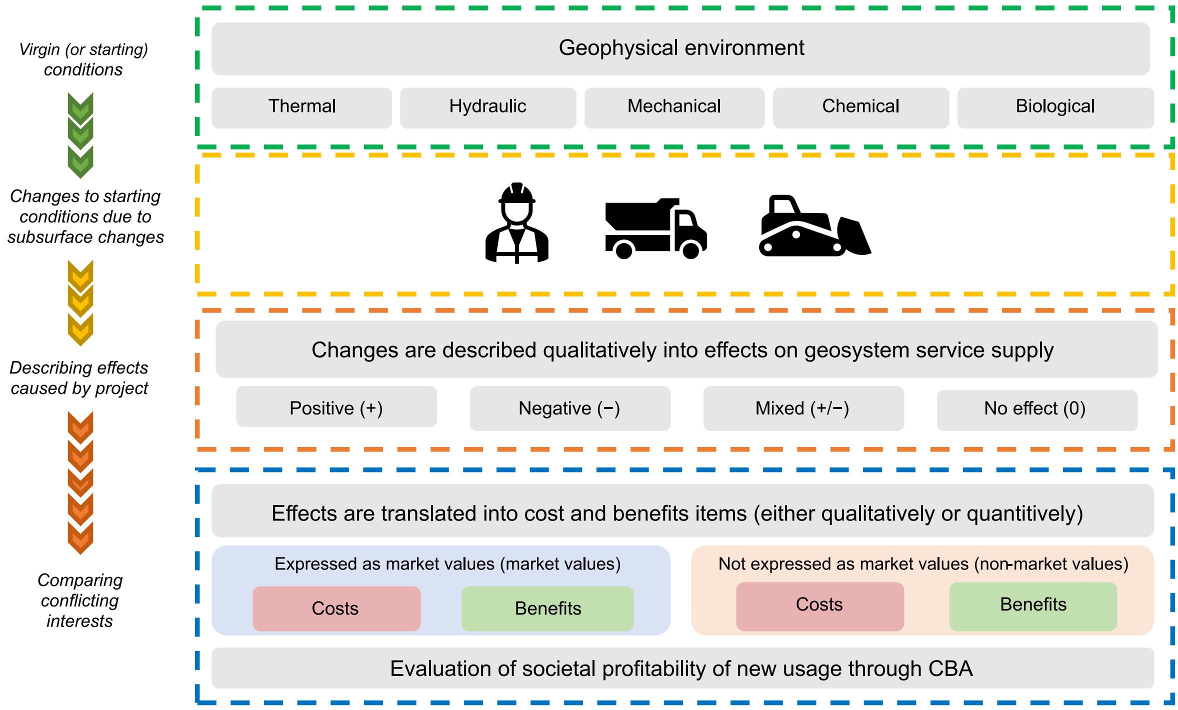


Figure 12: Illustrative framework for systematic overview of potential effects (e.g., externalities) caused by subsurface projects

The hypothetical case study emphasises that a cost–benefit analysis of the two cases may yield biased results if the values of non-market goods are excluded. This is particularly relevant for the benefits and costs associated with impacts on geosystem services, some of which are typically not traded on markets, while others are. A clear example is access to geomaterials, where extraction commonly results in market goods such as sand and gravel (benefit B8, ibid.). A less clear-cut case is reduced access to groundwater (cost C12, *ibid*.), which may result in goods like drinking water that are sometimes subject to market pricing, but not always, often due to regulatory frameworks. Other geosystem services are likely to relate exclusively to non-market goods, such as impacts on historical, recreational, or sacred sites (benefit B9, cost C13, *ibid*.). Hence, the main message from **Publication II** is that one cannot expect that information from transactions of market goods would give solid foundation for a cost–benefit analysis of the two cases. Furthermore, systematically reviewing all geosystem services may help ensure that none of the services related to the subsurface, particularly those typically classified as non-market, are overlooked and may be unintentionally affected by a given subsurface project.

Building upon the reasoning of van Ree and van Beukering (2016) and van der Meulen et al. (2016a), that argue that some of the supporting geosystem services should be viewed as final services as they relate to carrier functions of the geological substrate. Combined with the mapping of effects in theoretical case studies in **Publication II**, it makes sense that that some of the geosystem services synthesised **Publication I** should be reclassified as regulating and provisioning services rather than supporting services. For example, by reclassing these services, 'Stable platform to build on and within' to 'Regulation of stress and strain' and 'Subsurface space' as a provisioning service to ensure that these are included in subsurface assessments (since supporting, i.e. intermediate, services are excluded from common frameworks such as CICES by definition). Hence, moving forward chronically, from **Publication I & II**, four services were reclassified resulting in a new list of 22 services that are identified as interesting from a subsurface planning perspective. These 22 services are illustrated in Figure 13.

4.3 Geosystem Services from an Economic Point of View

One way to highlight how geosystem services are linked to society, i.e. how these services can be (or are) used to contribute to human welfare, is through a Geosystem Services Cascade model (GSC), akin to how the Ecosystem Service Cascade (ESC) has been used to link components of ecosystem services to social value (Zhang et al., 2022). The first cascading framework was proposed by Haines-Young and Potschin (2010), and it was regarded as a chain structure connecting landscape structural processes with benefits. Translating this chain structure in terms of geosystem services is relatively straightforward and an example is illustrated in Figure 14, where a coarse-grained sediment (e.g. a glaciofluvial deposit) can be used to infiltrate stormwater, that in turn can regulate the waterflow (i.e. slow down and more evenly distribute over time) which can in turn lower the risk of flooding, which can lead to lower damage costs and increased wellbeing of people.

Figure 13: Graphical representation of the geosystem services that have been identified as relevant for subsurface planning.

RESULTS & DISCUSSION

Table 2: Table of geosystem services, specific use and functions

	Geosystem service	Specific service	Specific use	Function
REGULATING	Regulation of stress and strain	Suitable construction conditions in the subsurface	Use of the subsurface as a construction medium	Ability of the bedrock to distribute stress and strain around tunnels and caverns
		Suitable construction conditions at the surface	Use of the subsurface as a stable platform or foundation	Ability of the terrain to distribute stress and strain as a result of surface load
	Regulation of groundwater quantity	Retention of stormwater	Use of the subsurface for infiltration and storage of water to reduce flooding risks	Ability to infiltrate and store stormwater
	Regulation of groundwater quality	Filtration of stormwater	Use of the subsurface to improve stormwater quality and reduce the cost of water treatment	Ability to filter and adsorb substances and particles from stormwater
	Regulation of temperature by the subsurface	Extraction of heat or cold from shallow [<400 m] geo-energy systems with drilled wells	Use of the subsurface to extract and store heat or cold	Ability to store and transfer heat and cold
SUPPORTING	Habitat provision	Providing habitats for wild subsurface organisms that support biodiversity	Provisioning of ecological conditions for sustaining populations of stygofauna and troglofauna that people use or enjoy	Geological and hydrological structures and processes govern the availability of suitable micro-habitats for subterranean fauna
	Groundwater dependent ecosystems	Providing habitats for wild surface organisms that support biodiversity	Provisioning of ecological conditions for sustaining populations of species that people use or enjoy	The subsurface governs the availability of groundwater that some ecosystems depend on
PROVISIONING	Metallogenic minerals	Source of mineral substances	Metals used in a wide variety of applications (e.g. steel)	Source of metallogenic minerals
	Industrial minerals	Source of mineral substances	Minerals used in a wide variety of applications (e.g. glass raw material)	Source of minerals with specific properties (e.g. low thermal conductivity)
	Construction materials	Source of mineral substances	Inorganic materials used for road and railroad macadam	Source of inorganic materials with specific properties (e.g. high impact strength)
			Inorganic materials used for concrete production	Source of inorganic materials with specific properties (e.g. good pumpability)
			Inorganic materials used for filling purposes	Source of inorganic materials with specific properties (e.g. suitable grain sizes)
	Ornamental resources	Source of mineral substances	Geomaterial used for decoration	Source of inorganic materials with desirable aesthetic properties
	Groundwater	Source of water	Use of drinking water from the subsurface	The ability of the subsurface to store and transmit water
			Use of water that can be used as a material (e.g. for cooling)	
	Geothermal resources	Source of energy	Using underground heat as an energy source	Underground temperature rises with increasing depth following the geothermal gradient
	Underground space	Source of space	Use of the deep subsurface to place vertical and horizontal constructions	Providing physical space (Underground cavity)
			Use of the near-surface subsurface to place vertical and horizontal constructions	
	Disposal and storage	Storage of CO_2 in porous media	Capture of CO_2 into long-term storage (CCS)	Providing physical space (Porous medium)
CULTURAL	Sacred and historical sites	Elements of nature that have symbolic, sacred or religious meaning	Spiritual, symbolic and other interactions with the natural environment	Providing elements of the environment that are important as symbols
	Iconic sites	Recreation (inclusive tourism)	Using the environment for sport and recreation	Providing suitable environments that are engaged with, used or enjoyed
		Contributing to aesthetic environments	Appreciation of the environment (e.g. cultural landscape linked to previous mining activities)	
	Geoscientific and educational sites	Scientific and educational resource	Intellectual interactions with the natural environment	Providing elements that are important for studying the evolutionary history of the earth and current geological processes

Note: Please note that not all the listed geosystem services are included in the table. No indicators were developed for services that mostly relate to underground risks rather than potentials.

Linking geosystem services to tangible benefits requires the specification of distinct use classes for each individual service. This approach reflects the methodology applied to ecosystem services within the CICES framework, where each service is described using a five-level hierarchical structure, with each level becoming progressively more detailed and specific. The purpose of this is twofold: first, to specify whether a service provides direct use, indirect benefits, or supports other services; and second, this information is used to ensure that appropriate mapping methods can be applied to said service. These clauses are developed to reflect the multiple services that a single geosystem service category may encompass. To exemplify, the service Provisioning of geomaterials can be further subdivided into three separate usages: (1) inorganic materials for road and railway ballast, (2) for concrete production, and (3) for materials for filling purposes. Clearly defining these specific uses is a crucial step in evaluating the service, as it helps identify the precise benefits provided, prevents double counting, and lays the groundwork for developing appropriate indicators for service assessment. Thus, a part of linking geosystem services to benefits is to specify specific use classes for each individual service. This is addressed in **Publication III**, where different uses linked to each individual geosystem service are presented as distinct use clauses (Table 2).

This specificity of the benefits provided by a given services is also necessary if one is to value said services. As highlighted in **Publication II**, some services often have well established market values, but for some other services one cannot expect that information from transactions of market goods would give full information on the benefits and value of that service to society (i.e. non-market services). By specifying distinct uses, information on these services value can be derived from other ways. Economic methods to value non-market services (see section 2.5) derived from ecosystems are available as a result of several decades of valuation research (Petrolia et al., 2021; Smith, 2006; Tinch et al., 2019). That said, valuation studies that have monetised changes in the supply of non-market geosystem services (and ecosystem services) due to changes in subsurface structures and processes are relatively scarce with 75 studies found (see **Publication II** for a review of valuation studies, and Figure 15 for an overview). This is especially true for some services, as some services have gained more attention in the reviewed literature than others. In broad terms, studies on provisioning services (that often have a well-established market value) have been favoured, whereas there are only a few studies that include aspects of cultural services. The lack of studies on the whole range of geosystem services suggests that the entire multifunctionally of the subsurface and the non-market goods and services therein has, as of yet, not been valued in scientific literature. Thus, it limits the possibility of benefit transfer from more well-studied areas or services.

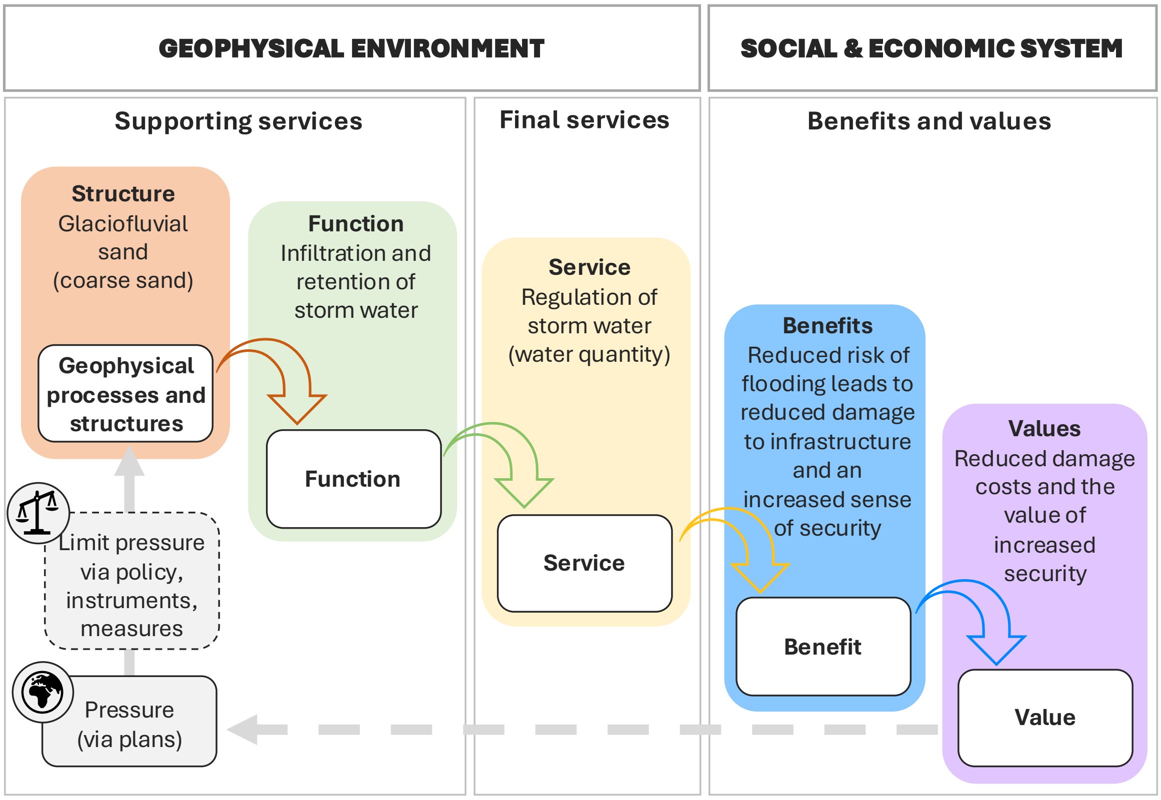
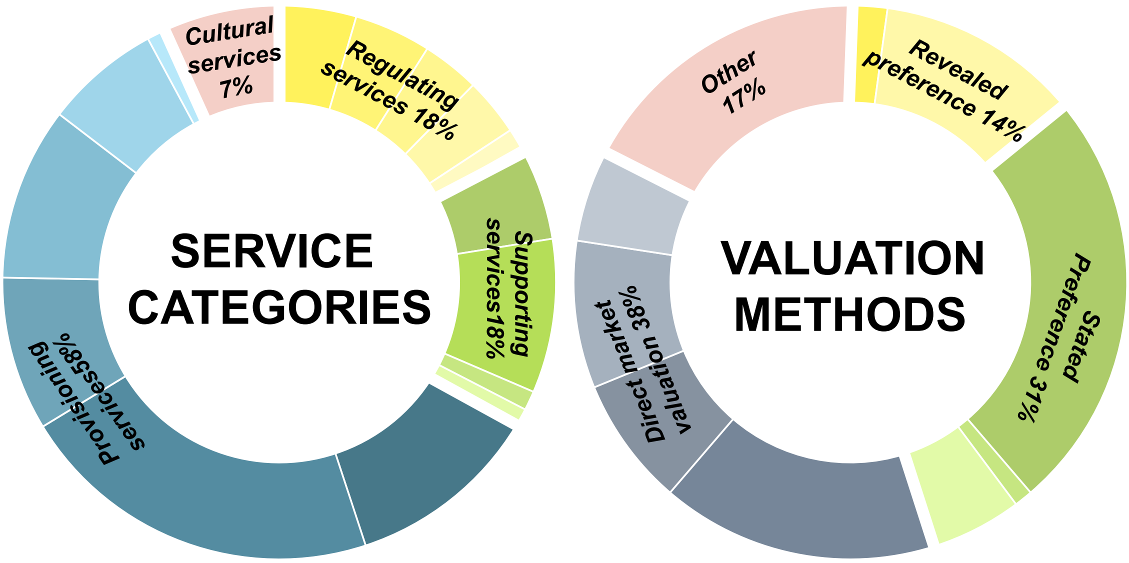


Figure 14: Cascade model for Geosystem service.
Note: Adapted from Haines-Young and Potschin (2010), modified to fit geosystem services.

The broad range of valuation methods used to assess the geosystem services (as indicated in Figure 15), suggest that there is untapped potential to utilise the valuation methods employed for ecosystem services. Indeed, it should be noted that geosystem services and ecosystem services often operate in tandem, and the loss of one can have significant implications for the other, potentially resulting in substantial societal impacts. The review of studies in **Publication II** highlights that 44% (37 in total) assessed changes in the supply of ecosystem services as a result of abiotic changes to the subsurface (i.e. changes to the geophysical environment). One such example is the study by Mazzotta et al. (2015), which investigated the potential welfare loss to freshwater anglers caused by mountaintop coal mining in West Virginia. Another example is the study by Hérivaux and Grémont (2019), which valued ecosystem services to support strategic groundwater preservation. As noted by Fox et al. (2020) and van Ree et al. (2017), the boundary between the geophysical and biophysical environment is often blurred, making it difficult to isolate their respective contributions and indeed, one could argue whether such separation is strictly necessary, given the strong interdependencies between abiotic and biotic processes in shaping eco- and geosystem services.

Nevertheless, the studies presented in **Publication II** that specifically have valued geosystem services demonstrate that these services can hold substantial societal value. For instance, Webber et al. (2006) highlight that 39% of surveyed tourists had visited the Isle of Wight specifically for its geological features. These visitors participated in a range of recreational activities, including hiking, walking, climbing, caving, mountain biking, surfing, and abseiling, and were also attracted to fossil collection sites. Their average daily expenditure was £73.86 and during 2004 to 2005 it is estimated that the total value of tourism on the Isle of Wight was estimated at £352 million, with the geological environment contributing approximately £11 million. By applying income and employment multiplier coefficients, Weber estimated that the geological environment generated between £2.6 million and £4.9 million in local income and supported between 324 and 441 full-time equivalent jobs per year.



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

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

Figure 15: Overview of valuation studies for geosystem services

4.4 Geosystem Services Indicators

As a prerequisite for developing geosystem services maps, in **publication III**, a set of nationwide indicators that can be used to map geosystem services in Sweden was developed. These indicators are based on indicators that were identified in the literature review (see Table 1 in **Publication III** for a comprehensive list of indicators found). The review revealed a diverse set of indicators, ranging from direct measurements (such as microorganisms and invertebrates) to proxies (such as the number of different genes measured in water samples), to indices (such as the Water Retention Index [WRI]) and composite indicators (such as the quantity of raw material produced). The literature review resulted in a gross list of 75 indicators that were deemed as useful for geosystem services mapping. However, the review also highlighted that a comprehensive set of indicators that capture the full range of services that the subsurface can potentially offer is currently lacking.

From this list of geosystem service indicators, a subset of indicators was singled out and further developed and adapted to a Swedish setting, resulting in curated list of 21 indicators for geosystem services. Table 3 shows the suggested indicators for each specific use related to a given geosystem service. (See Table 2 to 5 in **Publication III** for details on these indicators and assigned capacity classes). All of these indicators focus on the potential supply of services derived from the geophysical environment and were assigned a capacity class that describes their capacity to deliver a specific service (at a nationwide scale). This separation of the supply side (i.e. the physical environment) from the demand side (i.e. the social and economic system), rather than to use broad composite indicators, reflects that given environment can hold a certain potential to deliver a service that can fulfil societal needs and offer benefits, but that it might not currently be utilised. The rationale for distinguishing the supply side from the demand side is to enhance applicability in routine planning processes by accommodating a broader range of perceived benefits and values, that may evolve over time, to be accounted for (e.g. due to a changing climate, enacted policies or laws, or shifts in perceived importance between different locations). Which would ideally increase the operability of geosystem services in planning context.

Table 3: Table of geosystem service indicators

	Geosystem service	Specific use	Indicator(s) [measurement unit]
REGULATING	Regulation of stress and strain	Use of the subsurface as a construction medium	Rock type [-] Lineament density [n] Soft ground thickness [m]
		Use of the subsurface as a stable platform or foundation	Terrain classes [-]
	Regulation of water quantity	Use of the subsurface for infiltration and storage of water to reduce flooding	Permeable soils [-] Unsaturated zone thickness [m] Soil layer thickness [m]
	Regulation of water quality	Use of the subsurface to improve stormwater quality and reduce the cost of water treatment	Permeable and reactive soils [-]
	Regulation of temperature by the subsurface	Use of the subsurface to extract and store heat or cold	Thermal conductivity [W/(K m)] Lithological units [-]
SUPPORTING	Habitat provision	Provisioning of ecological conditions for sustaining populations of stygofauna and troglofauna that people use or enjoy	Lithological units (subterranean habitats) [-]
	Groundwater dependent ecosystems	Provisioning of ecological conditions for sustaining populations of species that people use or enjoy	Surface habitats [-]
PROVISIONING	Metallogenic minerals	Metals used in a wide variety of applications (e.g. steel)	Metallogenic belt [-]
	Industrial minerals	Minerals used in a wide variety of applications (e.g. glass raw material)	Metallogenic belt [-]
	Construction materials	Inorganic materials used for road and railroad macadam	Lithological units [-]
		Inorganic materials used for concrete production	Soil deposits [-] Lithological units [-]
		Inorganic materials used for filling purposes	Lithological units [-]
	Ornamental resources	Geomaterial used for decoration	Lithological units [-]
	Groundwater	Use of drinking water from the subsurface Use of water that can be used as a material (e.g. for cooling)	Groundwater extraction capacity [m^3/d]
	Geothermal resources	Using underground heat as an energy source	Geothermal gradient or Heat Flow [°C /km]
	Underground space	Use of the deep subsurface to place vertical and horizontal constructions	Underground infrastructure density [m^3/m^2]
		Use of the near-surface subsurface to place vertical and horizontal constructions	Building density [n/100m^2]
	Disposal and storage	Capture of CO_2 into long-term storage (CCS)	Saline sandstone aquifers [-]
CULTURAL	Sacred and historical sites	Spiritual, symbolic and other interactions with the natural environment	Geosite [-] Geotopes [-]
	Iconic sites	Using the environment for sport and recreation Appreciation of the environment (e.g. cultural landscape linked to previous mining activities)	
	Geoscientific and educational sites	Intellectual interactions with the natural environment	

Note: See tables 2-5 in **Publication III** for details on the indicators as well as the SM. Please note that some indicators are indexes of several parameters, e.g. permeable soils, unsaturated zone thickness and soil layer thickness. Legend: N/A Not Applicable, [-] dimensionless, [m] metre, [m3] cubic metre, [m2] square metre, [n] number of something, [d] day as in 24h.

4.5 Maps of Geosystem Services Potential

The geosystem service potential maps were developed in **Publication IV,** at the municipal scale, to demonstrate a methodology for creating such maps and to test their practical applicability for planning. Building on the work in **Publication III**, and the indicators suggested therein, a list of indicators related to geosystem services that are relevant to include in climate resilience planning were selected and adapted to the local context of Malmö municipality. In addition, suitability and accessibility indicators were introduced to capture not only the potential to supply a given service, but also its availability and the appropriateness of its utilisation based on a defined set of criteria. By combing the potential to supply a given service, with the accessibility and suitability, an effective potential that highlight how much of the inherent potential is available for use.

The developed maps serve to support climate resilience planning, as geosystem services can help to mitigate some of the climate-induced risks that are expected to increase due to climate change. For example, they provide heat and cold from the subsurface via geoenergy systems (see e.g. Erlström et al., 2016) or alleviate the adverse effects of heavy rainfall in urban areas through the infiltration of stormwater into the subsurface (see e.g. Carlsson et al., 2020; Lewis et al., 2006). To communicate (relevant) subsurface information, specifically how subsurface and the geophysical processes therein can contribute to climate mitigation strategies and how these services are spatially distributed, six thematic geosystem service maps were created in **Publication IV**:


Regulation of costal erosion


Extraction of heat and cold from the subsurface


Infiltration of stormwater


Access to subsurface space


Use of groundwater


Production of construction materials

The sensitivity to the capacity classes of the developed maps which indicates that all six maps maintain broadly consistent spatial patterns despite parameter changes, with internal disagreement remaining low to moderate (MDI ≈ 0.10–0.24). That said, the overall sensitivity, expressed as range-normalised average deviation (NA-RMSE), varies by service: where the maps for groundwater use is least sensitive (≈ 0.08), followed by coastal erosion regulation (≈ 0.10). Moderate sensitivity is observed for construction material extraction (≈ 0.20), subsurface space availability (≈ 0.21), and shallow geoenergy systems (≈ 0.22). Stormwater infiltration exhibits the highest sensitivity (≈ 0.33), driven by assumptions on unsaturated zone depth and filling material classification. Thus, most deviations stem from a few high-leverage parameters rather than cumulative minor changes.

It is worth noting that the most sensitive parameter for both regulation of coastal erosion and infiltration and retention of stormwater is related to anthropogenic filling materials, underscoring its importance. A significant portion of Malmö municipality (approximately 42%) is classified as consisting of anthropogenic filling material. Despite their prevalence, the filling materials in Malmö (and in many other cities) are poorly documented in the literature and cartographic materials. The need for greater attention to anthropogenic materials and urban soil contamination has been emphasised by previous research (Dijkstra et al., 2019; Taromi Sandström et al., 2024) and poses a significant and growing concern in urban planning worldwide.

The maps were also validated against independent data sets (see **Publication IV**). The validation indicates that the maps are reasonably robust; however, several notable limitations were identified. Foremost is the lack of independent datasets for certain services. For example, no validation was possible for subsurface space availability due to the confidentiality of underground infrastructure data. This reflects a broader challenge in geosystem service mapping, data scarcity and restricted access, which constrains both accuracy and transparency. Secondly, is the dependence on idealised geological conditions. Much of the geological information underpinning the maps is based on near-virgin conditions, which do not fully account for anthropogenic modifications. This limitation is particularly evident in the coastal erosion regulation map, where validation results diverged from expectations: areas with hard erosion measures often coincided with moderate or high potential classes. This mismatch illustrates how human interventions can obscure or alter the natural service potential, complicating validation efforts.

Using Malmö municipality as a pilot study, the developed geosystem service maps were subsequently tested with municipal civil servants to evaluate their usability and gather suggestions for improvement. Although Malmö already incorporates subsurface considerations in its planning, such as through the implementation of stormwater parks, feedback from the workshop evaluating the usability of the developed maps suggests that geosystem service maps could serve as a valuable tool in early-stage planning. Despite the novelty of the concept to many municipal civil servants, it was generally well received and appreciated for its communicative value, raising important issues early in the planning process that might otherwise be overlooked, thereby helping ensure that the subsurface is properly considered. However, participants also noted that the maps are better suited as communicative instruments than as direct planning tools. In this role, geosystem service potential maps act as boundary objects, conceptual and visual tools that facilitate dialogue across disciplinary and institutional boundaries, rather than serving as technical instruments for tasks such as site selection.

The findings underscore the potential benefits of integrating geosystem services into urban planning but also that geosystem service mapping is still in its early stages of development. In the case study, the integration could enhance Malmö's climate resilience by: (i) enabling more effective planning and optimised use of the subsurface, such as through the deployment of deep and shallow geo-energy systems and improved stormwater management; and (ii) promoting collaboration among stakeholders, thereby facilitating the implementation of innovative, subsurface-inclusive strategies for urban climate adaptation. Figure 16 and Figure 17 present two examples of such geosystem service maps, illustrating the services 'infiltration of stormwater' and 'provisioning of geomaterials'. However, it also highlights that to improve reliability and applicability of geosystem services maps, there is an urgent need for improved datasets and indicators, and novel datasets that focus on anthropogenic materials and human-made changes to geophysical structures and processes. In addition, future work should also explore mechanisms for data sharing and governance to overcome confidentiality barriers while safeguarding sensitive information.

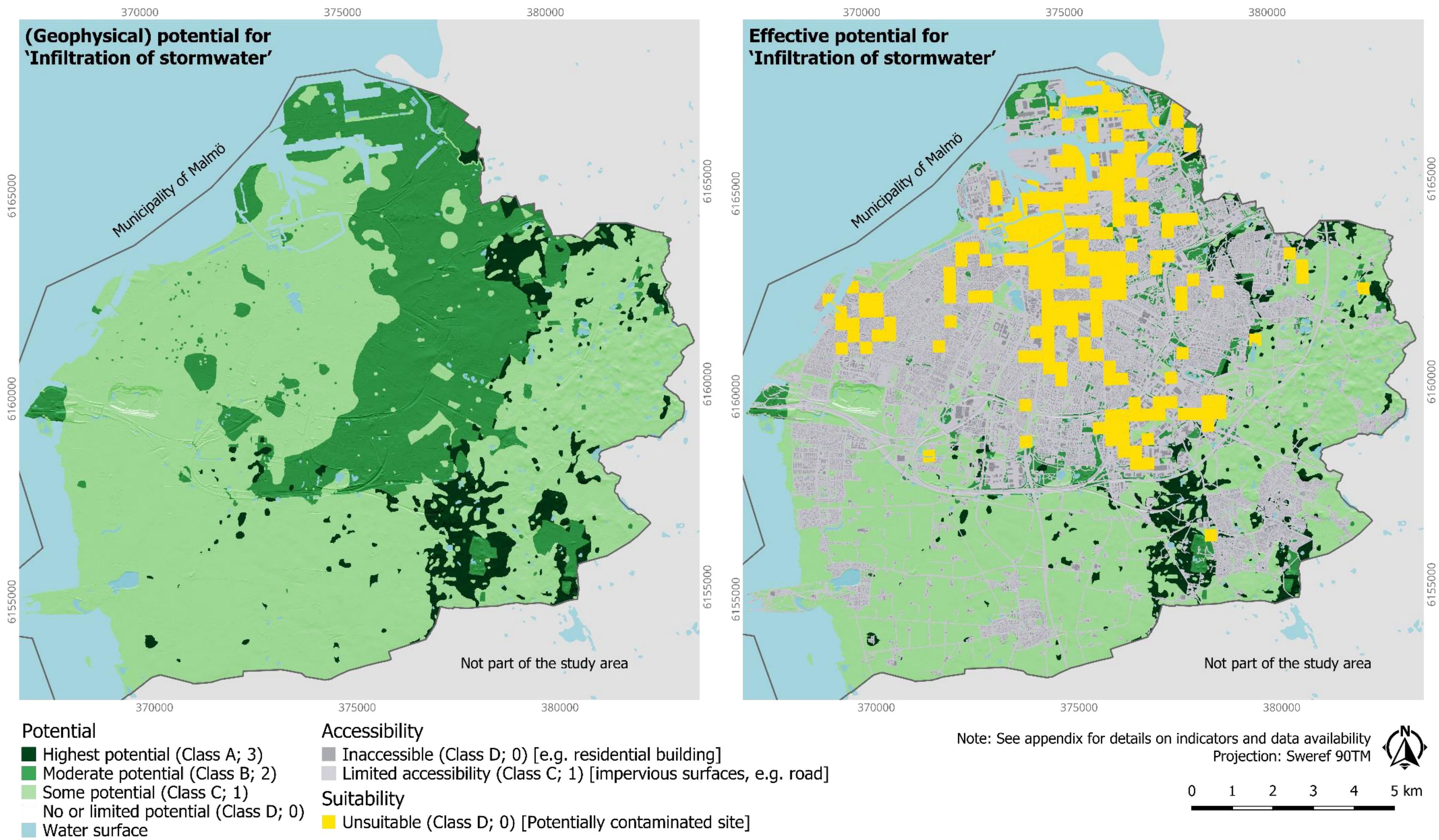


Figure 16: Example on geosystem service maps related to the service 'Regulation of water quantity' in relation to Malmö's climate resilience.
Note: See **Publications III-IV** and their Supplementary Materials (SM) for details on the indicators.

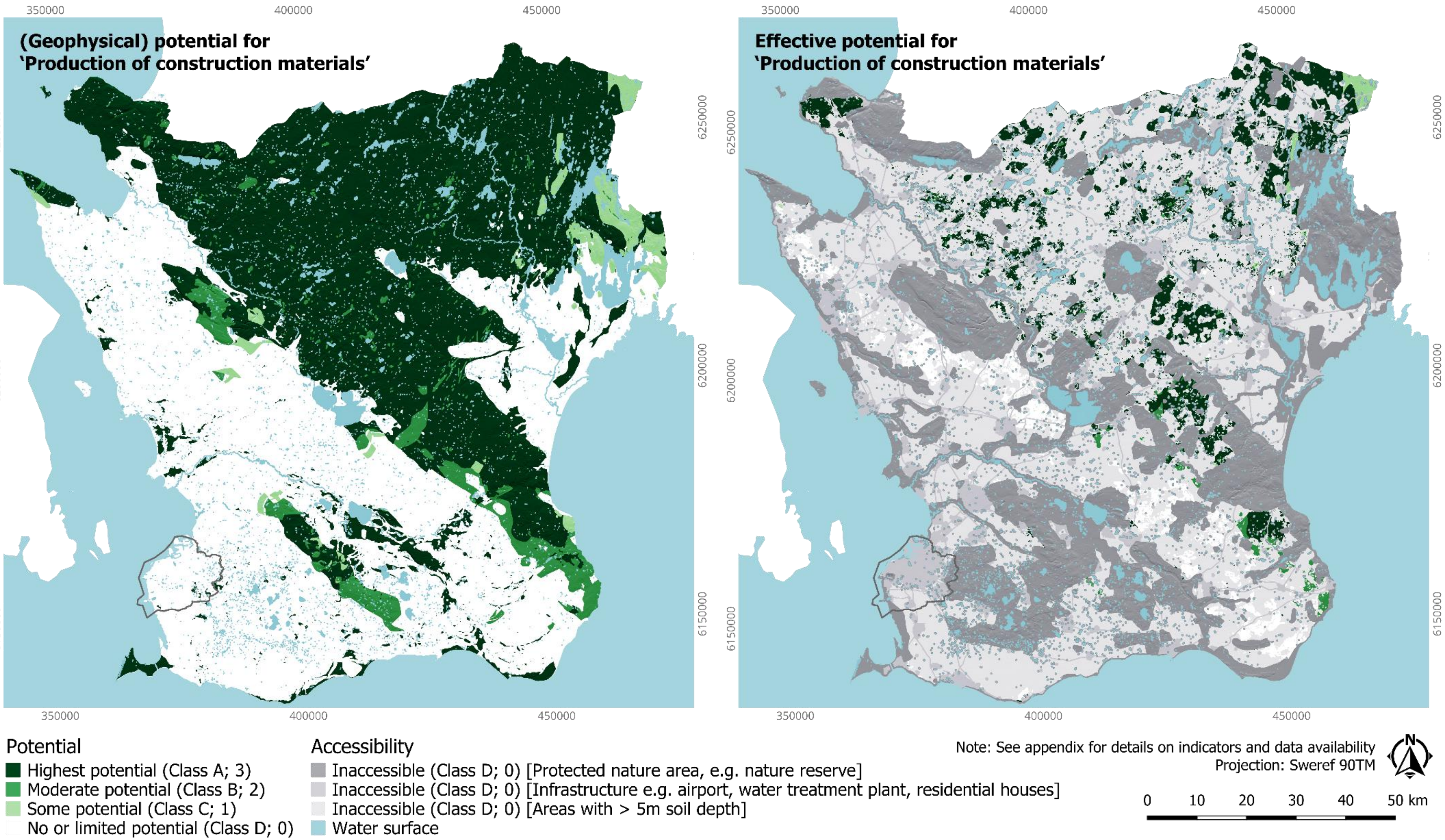


Figure 17: Example on geosystem service maps related to the service 'Provisioning of construction materials' in relation to Malmö's climate resilience
***Note**: See **Publications III-IV** and their Supplementary Materials (SM) for details on the indicators.*

Chapter 5
WIDER CONSIDERATIONS AND OUTLOOK

This chapter presents some wider considerations and outlook based on the work presented within this thesis.

The publications referenced in this thesis (**Publication I-IV**) highlight that the potential of the subsurface is not yet fully integrated into planning processes, but also that the concept of geosystem services offers a novel perspective by emphasising the benefits derived from the subsurface, thereby encouraging their greater inclusion in planning. In a planning context, geosystem services can provide a counterbalance to the often narrow perspective through which the subsurface is typically considered, such as its treatment solely as Urban Underground Space (UUS). Rather than focusing exclusively on extractive functions, for example the utilisation of underground space or the removal of geomaterials, this approach also promotes conservation-oriented objectives, such as safeguarding areas for stormwater infiltration or maintaining sites for educational purposes. Thus, the findings from **Publications I–IV** provide valuable insights into how planning of the subsurface could benefit from the systematic inclusion of geosystem services, as exemplified in a context of climate change adaptation the pilot study. These studies represent an early step towards establishing common standards and procedures, which are essential for operationalising the growing body of knowledge on geosystem services. As indicated in **Publication IV**, stakeholders found the geosystem service maps to be engaging and useful tools for discussion, particularly during the early stages of the planning process. Although the concept is viewed with interest and its potential is acknowledged, the concept remains relatively novel and its interpretation can vary depending on the audience and the specific issue being addressed (**Publication I**). Furthermore, there is a notable lack of research on how geosystem services could be incorporated into planning or policy frameworks, and what benefits such integration might yield.

5.1 Lessons Learned from the Implementation of Ecosystem Service

Taking the limited publication of geosystem services into account (see e.g. literature reviews in **Publication I-III**), it would be desirable for future research that explores diverse applications and geographical contexts to better understand both the benefits and the barriers to implementing geosystem services in planning. Furthermore, to advance the operationalisation of geosystem services, it is necessary to establish a unified definition and expand the literature on their quantification and societal benefits. Ideally, as discussed in **Publication I**, this definition would mimic the framework of the Common International Classification of Ecosystem Services (CICES), which includes both an ‘ecological clause‘ describing the biophysical output and a ‘use clause‘ outlining the resulting benefit. This approach would align with recent literature on environmental accounting, which emphasises the importance of focusing on final services rather than intermediate functions to reduce the risk of double-counting in decision-support tools and policy-making (Pascual et al., 2010).

The operationalisation of geosystem services can be further informed by insights from the ongoing development and application of the ecosystem services concept. Given the experiences of implementing ecosystem services (see ection 2.3 or e.g. Hysing, 2021; Saarikoski et al., 2018; Sang et al., 2021), it is pertinent to reflect on the intended role of geosystem services. Like ecosystem services, the geosystem services concept has the potential to highlight society's dependence on natural systems. However, to realise their full potential, it is necessary to progress beyond a purely conceptual understanding towards practical implementation, a transition that has proven difficult for ecosystem services, even within a comparatively supportive context such as Sweden (Hysing, 2021; Sang et al., 2021). To move beyond conceptual understanding, it would require that geosystem services concept is employed to address specific challenges and inform decision-making processes. And, as Hysing (2021) observes in relation to ecosystem services, there is a dire need for further research and practical examples that addresses competing social interests, ensure equitable spatial and temporal distribution of resources, and explore how geosystem service as a concepts can be institutionalised within legal frameworks, particularly if legal adoption is deemed a prerequisite for effective implementation.

5.2 Do We Need Yet Another Concept?

If many of the services discussed in this thesis are already included within existing ecosystem service frameworks such as CICES as highlighted in **Publication I**, is there truly a need to introduce a new concept? On one hand, it is logical to continue expanding the ecosystem services framework to ensure that all components of natural capital are represented. On the other hand, it is important to recall that the ecosystem services concept was originally introduced, in part, to address the fact that the contributions of ecosystems were often overlooked in assessments and decision-making. Expanding the framework too broadly may risk obscuring the very services it was designed to highlight (see e.g. the critique of differentiation between geosystem sevices and ecosystem services by Chen et al., 2024). The concern that broad frameworks can obscure some services is also to some extent echoed by Gray (2018) and van Ree et al. (2017), who note that while ecosystem services do include some geophysical contributions, the focus tends to remain on the biophysical aspects of nature, often at the expense of geophysical components. A similar issue has been observed in the discourse surrounding geodiversity and geotourism, where Ollier (2012) have pointed out that the term geotourism is on the verge of becoming so broad and all-encompassing that it loses its meaning.

To maintain both conceptual clarity and operational effectiveness, especially given the complexity of integrating all compartments of nature into a single framework, it may be more appropriate to develop targeted concepts for specific purposes. One such approach is to assess the contributions of each component of natural capital to human well-being in different themes (such focusing on underground planning, groundwater or climate), using the methodological tools developed over decades for ecosystem services. By leveraging the strengths of different disciplines and integrating the results of these individual assessments, while carefully considering interdependencies among the different systems spanning both geo- and biophysical environments, this approach could support more robust and well-founded decision-making. If implemented effectively, it would ensure consistency in terminology across service types and preserve the benefits of a systems approach, without diluting the more established ecosystem services concept. In this context, the concept of geosystem services can play a valuable role by explicitly acknowledging services that originate from the subsurface and the geophysical environment. An example from the field of water protection is provided by Gärtner et al. (2022), who introduced the concept of water system services (WSS), along with a proposed list of WSS that includes all biotic and abiotic services provided by a drinking water resource. This concept was developed to support decision-making related to water protection measures and illustrates how targeted frameworks can be operationally effective within specific domains.

Finally, the creation of distinct concepts related to specific themes can also have practical implications that could enhance their applicability. To illustrate, take the significant temporal difference in the origin and development of some of the ecosystem versus geosystem services as an example. As discussed in Chakraborty and Gray (2020) and in van Ree and van Beukering (2016), ecosystem services typically refer to features that have developed in relatively recent times, ranging from hundreds to thousands of years. In contrast, geosystem services may originate from present-day processes (e.g., groundwater recharge) or from geological features inherited from deep time, sometimes dating back to the early formation of the continental crust over 3 billion years ago. If both types of services are to be managed within a unified framework, these temporal differences should be explicitly acknowledged and managed. As discussed in **Publication II**, this temporal dimension could present challenges in the context of CBA, especially when multiple services are involved, some of which may be considered finite or non-renewable. In such cases, maintaining separate conceptual frameworks focused on specific themes may facilitate more appropriate methodological choices, such as selecting discount rates that account for vastly different time scales. This, in turn, could enhance the robustness and transparency of assessments and support more nuanced, context-sensitive decision-making. However, it should be noted that this approach does not fully resolve the issue, as significant variations in time spans may still exist within a given theme. In addition, spatial planning is inherently holistic in both nature and scope. Consequently, thematic ‘single-issue‘ problems are seldom problematised to a sufficient degree when weighed against diverse and often competing planning requirements. This highlights the importance of geosystem service mapping within a comprehensive perspective, consistent with principles of integrated spatial planning and governance. At the same time, thematic differentiation remains valuable for ensuring that attention is directed towards the most critical aspects under consideration and, as discussed in this thesis, can provide meaningful input to specific planning processes.

5.3 Critique of the Anthropogenic Perspective and Valuation of Services

The concept of ecosystem services, which frames nature's contributions to human well-being as 'services,' has faced sustained critique since its inception (e.g. Schröter et al., 2014). Broadly, these critiques centre around concerns about the concept's anthropocentric focus, potential for commodification of nature, and limitations in capturing the full complexity of ecological systems (e.g. Bekessy et al., 2018; Schröter et al., 2014; Wegner & Pascual, 2011). Given its conceptual similarity, the geosystem services framework is likely to be subject to similar concerns.

A primary critique is that by focusing predominantly on the benefits nature provides to humans, these frameworks risk excluding the intrinsic value of non-human entities (IPBES, 2022; Wegner & Pascual, 2011). Some argue that this reinforces an exploitative relationship with nature, rather than acknowledging the deep interdependence between humans and the natural world (Schröter et al., 2014). This critique is rooted in a long-standing debate within environmental ethics (Jax et al., 2013): should our actions be guided by an anthropocentric view that emphasises nature's instrumental value, or by a biocentric perspective that recognises its intrinsic worth? Nevertheless, for example Schröter et al. (2014) have argued that in an increasingly urbanised and technologically mediated world, particularly in the Global North, society has become disconnected from nature. This disconnection is reflected in the tendency to perceive nature primarily through an anthropogenic or instrumental lens. In this context, concepts like ecosystem and geosystem services can serve as important tools for challenging dominant paradigms, by offering a more holistic perspective. As such the concepts themselves could provide a means to reframe humanity's relationship with nature and bridge the growing gap between consumers and nature that sustain them.

Another concern is that framing nature's benefits as 'services' may lead to a overly optimistic portrayal of the subsurface (Craig-Thompson & Kuchler, 2025), combined with the commodification and marketisation of natural resources (Schröter et al., 2014). This can obscure their non-economic values and incentivise exploitation for short-term economic gain rather than long-term conservation. Indeed, placing economic value on nature is fraught with uncertainty (Tinch et al., 2019), ethical controversy (Hausman et al., 2016; Spangenberg & Settele, 2016) and potential counter-productivity in conservation efforts (Gómez-Baggethun & Ruiz-Pérez, 2011). However, it is important to recognise that decisions affecting nature are made every day, and that these often involves implicit value judgments (Schröter et al., 2014). Valuation, when done transparently, can help make these judgments explicit, enabling them to be scrutinised. It can also raise awareness of the relative importance of natural systems compared to human-made alternatives, and highlight the often-overlooked externalities of environmental degradation (Schröter et al., 2014). Monetary valuation thus can provide additional arguments for decision-making processes, but it does not replace ethical, ecological, or other nonmonetary arguments (IPBES, 2022; Schröter et al., 2014). Moreover, valuation does not necessarily require monetisation. The values of nature vary widely across knowledge systems, languages, cultural traditions, and environmental contexts, and a wide range of valuation methods can be used to reflect this diversity (IPBES, 2022).

Service-based frameworks have also been critiqued for oversimplifying the complex and interconnected nature, potentially overlooking indirect and cascading effects (Norrman et al., 2024; Schröter et al., 2014). For example, the indicators proposed in **Publication III** and their application in **Publication IV** illustrate instances where this complexity is substantially simplified to accommodate data availability and practical constraints. Moreover, some services are inherently difficult to quantify or value, which can result in incomplete assessments and skewed decision-making (IPBES, 2022). Indeed, the review of valuation studies in **Publication II**, highlighted that for some services no or only a limited number of studies have been carried out. While these concerns are valid, it is also true that some level of abstraction is necessary to make complex systems intelligible and actionable for policymakers. These frameworks are not intended to be exhaustive representations of reality, but rather tools to translate complexity into policy-relevant insights. Their strength lies in their ability to provide clarity and usability, thereby supporting more informed decisions (Schröter et al., 2014). That said, as pointed out in e.g. Schröter et al. (2014) and Potschin et al. (2016), many frameworks now integrate mixed-method approaches, combining biophysical, economic, and socio-cultural dimensions to provide a more holistic view. This evolution reflects an increasing awareness of indirect and cascading effects, which are being addressed through scenario modelling, stakeholder engagement, and adaptive management strategies (Schröter et al., 2014). As the concept of geosystem services becomes more clearly defined and operationalised, future research may need to explore similar integrative approaches.

In short, geosystem services, like ecosystem services, are evolving tools that aim to balance complexity with practicality. Their value lies in their capacity to inform decision-making while remaining adaptable to new knowledge and perspectives. Geosystem services specifically, has the potential to highlight the importance of the subsurface and foster interdisciplinary communication. However, it is important to recognise the limitations. The concept alone is insufficient to drive transformative societal change, but what is essential is not the term itself. It is the underlying perspective it represents, namely, the recognition that nature (including all parts of it) is instrumental to human well-being and quality of life.

5.4 Outlook on Geosystem Service Indicators and Maps and How They Fit into a Planning Context

The development and application of geosystem service indicators represent a promising yet underexplored frontier. While the conceptual foundation for environmental indicators is well established, both the theoretical and practical implementation of geosystem service indicators remain in their early stages. To date, only two known attempts to spatially map geosystem services (Stanley et al., 2023; Tognetto et al., 2021) exist outside the publications appended to this thesis. In contrast, there is a substantial body of literature dedicated to the development and application of ecosystem service indicators, where various datasets and methodologies have been extensively developed, applied, tested, and reviewed (see e.g. Czúcz et al., 2018; Müller et al., 2016 for examples on indicator lists for ecosystem services). A significant proportion of these indicators are composite indicators, which aggregate multiple sub-indices, each representing different ecosystem services (e.g., air quality regulation, biodiversity conservation) or land use types, into a single index (Potschin et al., 2016).

Recent research on ecosystem service indicators have focused on distinguishing between indicators of ecosystem service potential, actual flows (i.e., services that are effectively used), and societal demand (see e.g. Andersson-Sköld et al., 2018; Baró et al., 2016; Czúcz et al., 2020). The advantage of separating these aspects lies in the flexibility of the methodology, allowing it to be adapted to diverse planning contexts, and thus increase the practical utility of indicators in the routine planning processes and trade-off assessments (Andersson-Sköld et al., 2018). In **Publications III** and **IV**, a similar methodological approach was adopted, differentiating between the potential to supply a given service and the availability and suitability for its use. Although not included in these publications, this framework should be further extended to incorporate the perceived value of the benefits provided by each service in a specific context.

To exemplify why this could be beneficial, stormwater infiltration may be a highly valuable service in densely populated urban areas, where impervious surfaces limit natural drainage and the consequences of flooding may affect many. In contrast, suburban or rural areas typically have more permeable surfaces that facilitate natural infiltration and reduce runoff, and the consequences of flooding may affect fewer people. The mapping methodology needs to be flexible to accommodate both these cases. Additionally, given that planning often involves political considerations, it is essential to accommodate differing perspectives on service prioritisation and valuation if mapping is to be integrated into the planning process.

While geosystem service indicators can assist planners in quantifying and visualising the benefits humans derive from nature, there is growing concern within the scientific and policy-making communities regarding the actual utility of such indicators in decision-making. For example, van Oudenhoven et al., 2018 have raised concerns in relation to ecosystem service indicators, which are well-established but often fail to influence planning decisions meaningfully (van Oudenhoven et al., 2018). Moreover, research on the role of ecosystem services in planning in Sweden (Hysing, 2021; Sang et al., 2021) reveals that although indicators are frequently developed and applied to map ecosystem services in scientific literature, they rarely have practical implications in the planning process. As such. the discourse surrounding indicator suitability has largely remained within academic circles, focusing primarily on scientific credibility and precision rather than practical applicability (van Oudenhoven et al., 2018). This further emphasises a critical lesson for geosystem service mapping: indicators must be designed with usability in mind. To be integrated into routine planning processes, they must not only be scientifically robust and operationally feasible but also offer tangible value to the planners expected to use them. Here geosystem services can contribute by packaging geological and geomorphological knowledge, often in the form of maps or models, into formats that are more accessible and relevant to planning professionals. Nevertheless, the effectiveness of any indicators ultimately depends on their ability to support real-world planning decisions, and currently few if any studies have examined this aspect.

Looking ahead, it is also important to recognise that geosystem services face challenges that ecosystem services have already begun to address. Here, a key issue is data availability. While biodiversity and ecosystem-related data are relatively abundant (Potschin et al., 2016), detailed and high-resolution subsurface datasets remain limited (see e.g. Chaminé et al., 2016; Yan et al., 2021). In addition, unlike ecosystem services, which often focus on surface-level processes, geosystem services are often inherently linked to the subsurface (see e.g. **Publication I**). This presents a unique challenge for urban planners and designers: making the invisible visible (Admiraal & Cornaro, 2016; van der Meulen et al., 2016b). The interdependence with geological conditions, combined with the need to visualise what exists below ground, what is possible, and how subsurface systems function, requires approaches that differ significantly from traditional surface-based planning methods that typically relies on 2D maps (Admiraal & Cornaro, 2016).

While 2D maps can incorporate depth data (see e.g. the soil depth map used in **Publication IV**), three-dimensional (3D) modelling has become a cornerstone in modern geological sciences and civil engineering and authors such as Admiraal and Cornaro (2016) and Eilola et al. (2023) have argued that physical planning should increasingly adopt a 3D, or even 4D, approach. Ideally, these should include reliable methods for representing and managing information uncertainty, which remains a persistent and significant challenge for geospatial data. To remain relevant for future spatial planning, geosystem service frameworks should be adapted to fit within 3D or 4D models, thereby enhancing the accessibility and applicability of geological and geomorphological information for planning professionals.

Although the indicators and maps presented in **Publications III** and **IV** are relatively simple 2D representations, they serve as important stepping stones for future research. **Publication IV**, in particular, highlights a replicable methodology for developing geosystem service potential maps that systematically link geophysical environments to specific services. Given the lack of guidance in the literature on implementing geosystem services, and the shortage of practical tools to support their integration into planning processes, this thesis and its associated publications make a contribution to the emerging discourse and provides a foundation for future research aimed at increasing the operability of geosystem services in planning processes.

Chapter 6
CONCLUDING REMARKS

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

In the following bullet points, the most important findings from the thesis and the appended publications are summarised in relation to the aims and objectives of the thesis.

1 By reviewing and synthesising relevant definitions of geosystem services in **Publication I**, a foundational understanding of the concept and its potential connection to subsurface planning has been established. Two main definitions emerged: (a) geosystem services as services derived from abiotic nature, and (b) services originating specifically from the subsurface. From a subsurface planning perspective, the second definition may be easier to communicate and operationalise.

2 The framework for systematic assessment of the effects of subsurface projects on geosystem services, and the translation of this information into a qualitative cost–benefit analysis context in **Publication II**, provides a foundation for a systematic approach to assess effects caused by underground projects. By systematically evaluating the effects caused by the underground projects, it is revealed that some services previously classified as supporting services can, in certain contexts, be regarded as final services. Consequently, a reclassification of these services and an updated list of services is suggested to ensure they are not excluded from assessments that often focus solely on final services. The list of geosystem services is also a significant result in its own right, as it can function as a practical checklist to ensure that the subsurface, together with all its structures and functions, is considered in various assessments.

3 A qualitative cost–benefit analysis for the two underground projects discussed in Publication II also underscored that market transactions alone cannot be expected to provide comprehensive information regarding the value of the subsurface. This must be supplemented with non-market services. That said, the compilation of valuation studies in **Publication II** highlighted the monetary value of non-market geosystem services, providing an overview of their economic significance, which can be substantial. However, it has also revealed a significant research gap: overall, relatively few studies exist on this subject, and for some services only a very limited selection of valuation studies is available. Consequently, further research in this area is not only warranted but urgently required to fully describe the value of the services that the subsurface provide to society.

4 The development of indicators in **Publication III** to assess and visualise the potential for delivering specific geosystem services has equipped stakeholder with an interest in the subsurface with prerequisites for developing simple tools for discussing and including the subsurface in to planning processes. All but two of the suggested indicators can be directly applied using Swedish and Nordic open-access databases and maps to visualise the potential supply of specific geosystem services in the study setting. A key feature of the developed indicators is the systematic separation of indicators into supply and demand, with the indicators proposed here focusing on potential supply. This approach ensures that the indicators are sufficiently generic to allow broad applicability and, importantly, enables their later integration with value-based indicators tailored to specific contexts.

5 The creation of maps of geosystem services potential and their application in climate resilience planning in **Publication IV** demonstrate the practical usability and some challenges of these tools in a planning context. Feedback from the workshop indicated that, although the concept was novel to municipal civil servants, it was generally well received and appreciated for its communicative value rather than as an instrument that could directly inform the planning process. By raising important issues early in the planning process that might otherwise be overlooked, it can help ensure that the subsurface is properly considered.

In summary, this thesis advances the understanding of geosystem services within the context of subsurface planning and provides methodologies and tools that can be utilised in future research and planning efforts. The thesis also points out research gaps that could be addressed to ensure consistency in terminology and classification of geosystem services, as well as to increase the operability of the concept. Overall, the findings and methodologies presented here could serve as a resource for both researchers and practitioners interested in the concept of geosystem services.

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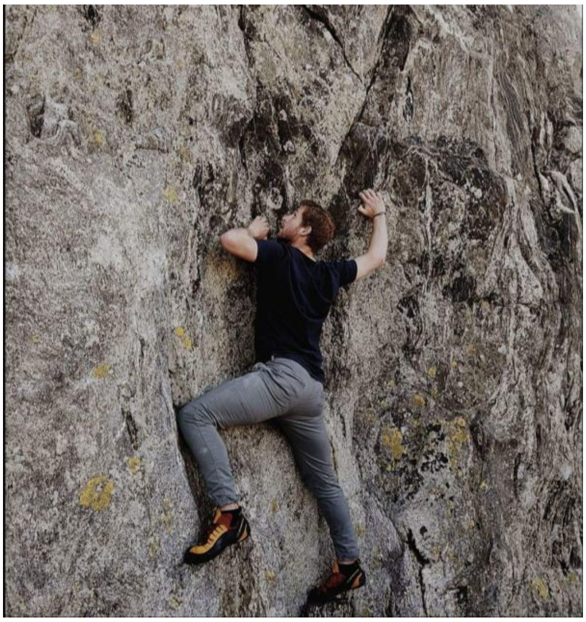

I wish you all the best going forward.
Cheers,
Emrik Lundin Frisk

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