THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Decision support for sustainable groundwater management in underground construction

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Gothenburg, Sweden 2025

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Doktorsavhandlingar vid Chalmers tekniska högskola
ISSN 0346-718X
Series number: 5815
ISBN: 978-91-8103-358-8
DOI: https://doi.org/10.63959/chalmers.dt/5815

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Cover:
The cascade model

Chalmers, Reproservice
Gothenburg, Sweden 2026

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ABSTRACT

Groundwater systems support vital services and benefits to human well-being, but underground construction and the associated leakage of groundwater may impair the capacity of these systems to perform their essential functions and provide vital services. Leakage of groundwater into underground constructions must therefore be managed to reduce the risk of negative impact due to lowering groundwater levels in the surrounding hydrogeological environments. The overall aim of this thesis is to develop methods and present examples of how the well-established risk management process according to the International Organization för Standardization (ISO) can be applied to manage hydrogeological risks in a sustainable and transparent manner. Four studies were carried out and specific contributions from the studies include: a risk-management framework for developing decision support for leakage management (Paper I); a method and example for identification of leakage induced risks (Paper III); a method for translating risks and risk-mitigation measures into relevant cost and benefit items to be valued in a risk-based decision analysis (Paper II and III); model chains for risk analysis and risk evaluation using CBA and CEA that allow for updating when new information is available (Paper II and IV); and methods for monetization of costs and benefits (Paper II and IV). Results from the studies in this PhD thesis all constitute key aspects of a successful and transparent risk management process and thus decisions on implementation of risk-mitigation measures. The thesis also provides a discussion on the importance of probabilistic modelling and transparency when developing models, the need to consider relevant boundary conditions that result in limitations regarding possible decisions, the limitations of using CBA or CEA for risk evaluation, as well as the task of taking a decision based on the decision support provided by the framework and methods presented in this thesis. Recommendation on how to apply the framework and the methods is also presented. As a final part of the thesis, the main conclusions from the thesis are presented and the need for further studies and developments of methods are discussed.

LIST OF PUBLICATIONS

This thesis contains the following publications appended to the thesis:

I. Merisalu, J., Sundell, J., & Rosén, L. (2021). A framework for risk-based cost–benefit analysis for decision support on hydrogeological risks in underground construction. *Geosciences*, *11*(2), 82. https://doi.org/10.3390/geosciences11020082.

II. Merisalu, J., Sundell, J., & Rosen, L. (2023). Probabilistic cost-benefit analysis for mitigating hydrogeological risks in underground construction. *Tunnelling and Underground Space Technology*, *131*, 104815. https://doi.org/10.1016/j.tust.2022.104815.

III. Merisalu, J., Söderqvist, T., Volchko, Y., Sundell, J., & Rosén, L. (2025). Identification of benefits and costs from the reduction of hydrogeological risks in underground construction. *Engineering Geology*, 108308. https://doi.org/10.1016/j.enggeo.2025.108308.

IV. Merisalu, J., Söderqvist, T., & Rosén, L. (2026). Cost-effectiveness analysis as decision support for groundwater leakage management in tunnels. Manuscript aimed to be submitted to journal in spring 2026.

Division of work between the authors:

Paper I: Conceptualization, J.M., J.S. and L.R.; Funding acquisition, J.M. and L.R.; Supervision, J.S. and L.R.; Project administration, L.R.; Visualization, J.M.; Writing—original draft, J.M.; Writing—review and editing, J.M., J.S., and L.R.

Paper II: Conceptualization, J.M., J.S. and L.R.; Funding acquisition, J.M. and L.R.; Supervision, J.S. and L.R.; Methodology, J.M., J.S. and L.R.; Software, J.M.; Formal analysis, J.M.; Investigation, J.M. and J.S.; Visualization, J.M.; Writing—original draft, J.M.; Writing—review and editing, J.M., J.S. and L.R.; Project administration, L.R.

Paper III: Conceptualization: J.M., T.S., Y.V., and L.R.; Funding acquisition, J.M., T.S., J.S. and L.R.; Supervision; T.S. and L.R.; Formal analysis, J.M. and T.S.; Investigation, J.M.; Visualization, J.M.; Writing – original draft, J.M. and T.S.; Writing – review and editing, J.M., T.S., Y.V., J.S. and L.R.; Project administration, J.M., T.S. and L.R.

Paper IV: Conceptualization, JM., TS. and L.R.; Funding acquisition, J.M., TS. and L.R.; Supervision; T.S. and L.R.; Methodology, J.M., T.S. and L.R.; Software, J.M.; Formal analysis, J.M.; Investigation, J.M.; Data Curation, J.M. and T.S.; Visualization, J.M.; Writing—original draft, J.M.; Writing—review and editing, J.M., T.S. and L.R.; Project administration, L.R.

Other work and publications not appended to this thesis:

Merisalu, J., & Fransson, A. (2018). Hydrogeological Reference Conditions for Assessment of Environmental Impact and for Grouting Design. In *ISRM International Symposium-Asian Rock Mechanics Symposium* (pp. ISRM-ARMS10). ISRM. 978-981119003-2 (ISBN).

Merisalu, J., & Rosén, L. (2020). *Villkorsutformning för grundvattenbortledning vid undermarksbyggande*. Tech. Rep. No. ACE 2020: 11. Chalmers University of Technology, Department of Architecture and Civil Engineering, Gothenburg, Sweden. https://research.chalmers.se/publication/516949/file/516949_Fulltext.pdf.

Merisalu, J. (2021). *Managing hydrogeological risks in underground construction* [Licentiate thesis, Technical report 2021:10]. Chalmers University of Technology, Department of Architecture and Civil Engineering. https://research.chalmers.se/en/publication/527333.

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.

Axéen, S., Merisalu, J., Haaf, E., & Rosén, L. (2025). Evaluating effects of geological conceptualization on simulated pore pressure reduction from groundwater leakage to excavation. In *Tunnelling into a Sustainable Future–Methods and Technologies* (pp. 938-944). CRC Press. http://dx.doi.org/10.1201/9781003559047-121.

Axéen, S., Merisalu, J., Haaf, E., & Rosén, L. (2026). Impact of geological conceptualization in predicting pore pressure reduction from urban excavations. *Engineering Geology*, 108601. https://doi.org/10.1016/j.enggeo.2026.108601.

AKNOWLEDEGEMENTS

The financial support from the Swedish Rock Engineering research foundation, BeFo (project 414 and 422), the Swedish transport administration (2020/92852), and the Swedish Research Council for Sustainable Development Formas (contract no 2022-01074) are gratefully acknowledged.

I would like to thank all my present and former colleagues at the division of Geology and Geotechnics for providing great company throughout the years. Among these colleagues I would like to say an extra thank you to my main supervisor, Lars Rosén, for his continuous guidance, encouragement, support and academic supervision throughout this project and to Jenny Norrman for the moral support and for taking the role as my examiner. Also, outside but almost inside of Chalmers, a big thank you to Jonas Sundell who guided me into the field of subsidence risks early in my studies and a big thank you to Tore Söderqvist for making me think outside the narrow box of underground construction. Finally, I would like to say thank you to everyone at Trafikverket who have been helpful with the case studies used for method development and exemplification in the papers appended in this thesis. No one named, no one forgotten.

Gothenburg, November 2026

Johanna Merisalu

TABLE OF CONTENS

1 Introduction

The first chapter provides the background to the thesis. The aim and objectives are presented, and the scope of the work is specified. Important limitations of the thesis are also presented.

1.1 Motivation

Underground construction plays a vital role in addressing the spatial, environmental, and infrastructural challenges of modern urbanization. As the ground surface becomes increasingly developed, subterranean development offers a viable alternative for accommodating essential infrastructure such as transportation networks, utility systems, and public facilities (Broere, 2016; Huggenberger et al., 2011). Tunnels are also often necessitated by the topographical constraints of a region, particularly in mountainous, hilly, or densely urbanized areas where surface routes are impractical or environmentally disruptive. In such settings, subsurface construction enables efficient connectivity while minimizing landscape alteration. Placing infrastructure below ground has many benefits, e.g., reduced barrier effects on wildlife and humans, freeing space for development on the surface, reduced travel time, reduced air pollution, and reduced noise pollution (Anciaes et al., 2020; Ayalon et al., 2016; Broere, 2016; Cowie et al., 2012; Forman et al., 1998; Rico et al., 2007; Volchko et al., 2020).

Although there are many benefits of locating infrastructure below ground, it often comes with a higher cost compared to building the same facility on the ground surface (Attinà et al., 2018). Construction below the groundwater table is also often associated with groundwater leakage and potential environmental impacts due to groundwater level decline in aquifers in hydraulic contact with the construction. This subsequently results in a wide variety of risks to both humans and the environment and thus potential loss of vital services supporting human wellbeing (van der Gun, 2021). Examples of objects at risk are subsidence-prone buildings and infrastructure (Boone, 1996), groundwater extraction systems (Chae et al., 2008), groundwater ecosystems (Stumpp et al., 2013), archaeological sites (Holden et al., 2009), and groundwater-dependent ecosystems (Behzad et al., 2022; Kværner et al., 2008).

To preserve benefits to society provided by an undisturbed hydrogeological setting, it is essential to manage the risks associated with groundwater leakage and subsequent groundwater level decline. Mitigation strategies include sealing techniques (Luciani & Peila, 2019; Panthi & Nilsen, 2005), artificial recharge methods (Cashman & Preene, 2001; Zeng et al., 2019; Zheng et al., 2019), and targeted interventions such as structural reinforcement of subsidence-sensitive buildings (Díaz et al., 2018; Ding et al., 2015). However, implementing measures are often expensive, and the economic effects in society of the measures must be considered for efficient prioritization of society's limited resources.

Decisions on mitigation measures and design of the underground construction must always be made under uncertainty (Einstein, 1996, 2004). Uncertainty is an inherent feature of underground construction, and it persists throughout all phases of a construction project. However, its magnitude is not static. As the project advances and more information becomes available, the understanding of subsurface conditions improves, thereby reducing uncertainty over time (Lundman, 2011; Merisalu et al., 2021). This calls for modelling of the system behavior that can be updated as more information of the system is retrieved. The chain of events that is initiated by a leakage and that causes consequences such as negative impact on groundwater systems and thus on the services and benefits that the system provides (Figure 1) also calls for usage of multiple models, each aiming at representing different parts of the chain. Thus, all events from leakage to effects on human wellbeing must be accounted for in the analysis.

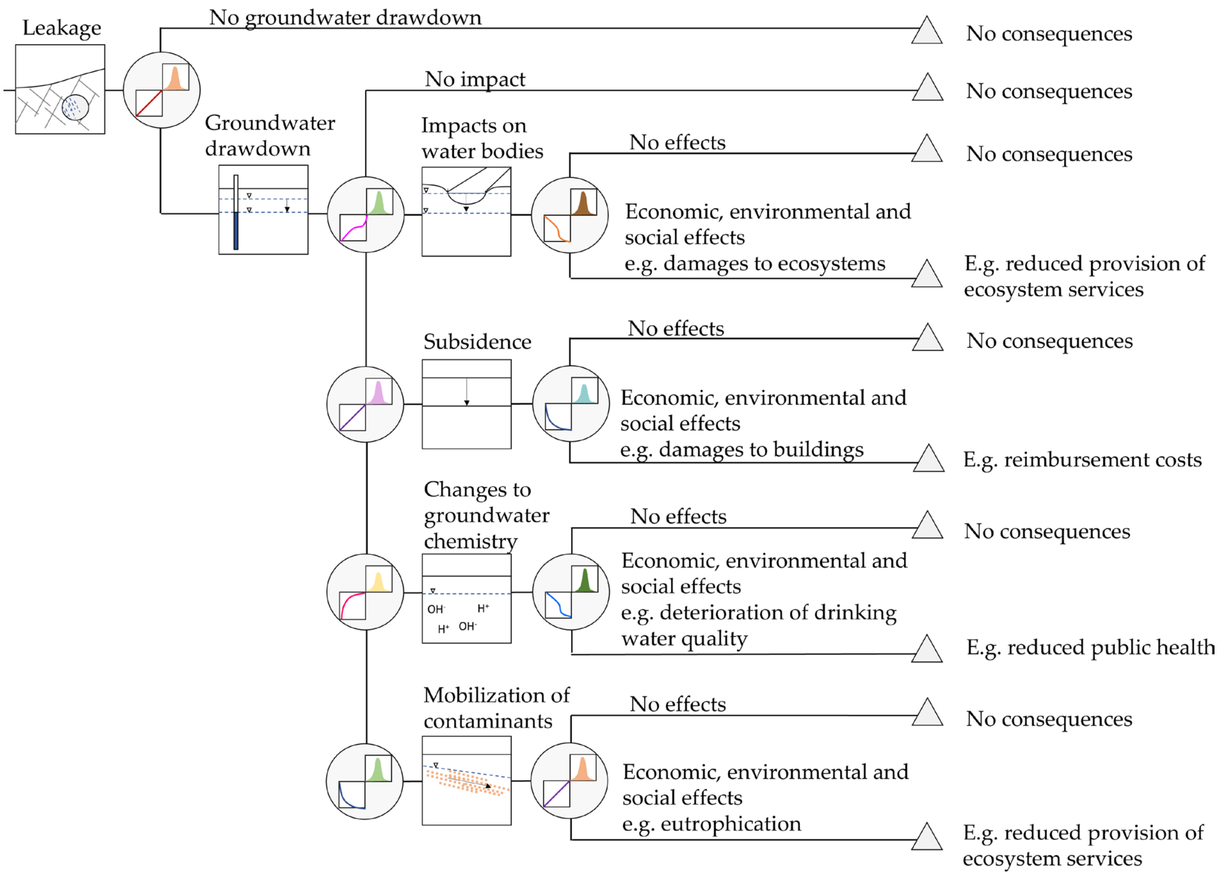

Figure 1. Event tree illustrating the cause–and effect chain for several examples of effects and consequences caused by leakage into an underground facility. The circles represent the complex relationship between the different events of the chain. The events can have economic, environmental, and social effects, which in turn result in consequences. The figure was published in Paper I (Merisalu et al., 2021).

Given the complex interplay between underground construction and hydrogeological systems, managing associated risks in a sustainable and informed manner is both a technical and societal imperative. This calls for a structured risk management process that not only addresses uncertainty but also integrates environmental, economic, and social sustainability considerations. While general risk management principles are well established, most notably through the ISO 31000 framework (ISO, 2018), their application to hydrogeological risks in underground construction remains fragmented. In practice, risk assessments often focus on individual hazards or isolated impact pathways, and economic evaluations of mitigation measures are frequently incomplete, failing to account for cascading effects from groundwater leakage to environmental and societal consequences. The need for a structured and adaptive approach is further emphasized by the Observational Method (as recommended in Eurocode 7) (1997-1, 2004; Peck, 1969), which highlights the importance of continuously updating models and decisions as new information becomes available during construction. However, existing applications of risk-based decision analysis in underground construction have largely focused on specific issues such as ground settlements as demonstrated by Sundell (2018), or cost and time overruns demonstrated by e.g., Einstein (2004), and construction methods demonstrated by e.g., Eskesen et al. (2004). There remains a clear need to extend such approaches to include hydrogeological processes and a broader set of environmental and societal impacts, as well as methods for systematically identifying cascading risks and evaluating them within a comprehensive risk-based decision analysis framework.

In this thesis, a framework together with examples on application is presented for risk-based decision analysis as decision support for hydrogeological risk-mitigation measures. Given the ethical basis for cost-benefit analysis, this thesis is thus grounded in consequentialism ethics, meaning that the rightness of an action or decision is judged by its consequences (Anscombe, 1958). It also adopts a utilitarian and anthropocentric view meaning that it has a human-centered perspective that focuses on human wellbeing where an action or decision is judged on the basis of its contribution to overall utility, i.e. human wellbeing now and in the future (Farley et al., 2020; Imran et al., 2014). The ambition in this thesis is to, as far as practically possible, quantify human well-being in monetary terms. The opposite of consequentialism ethics is deontological ethics where actions are judged based on a set of principles or moral duties (e.g., justice and equity) (Howarth, 1995). Deontological ethics are not adopted in this thesis. However, the framework for risk-based decision analysis presented in this thesis has the potential to be expanded to include e.g. ethical or equity conditions as boundary conditions for the analysis when setting the scope of the analysis.

1.2 Aim and objectives

The overall aim of this thesis is

> *to develop methods and present examples of how the well-established risk management process according to the International Organization for Standardization (ISO) can be applied to manage hydrogeological risks in a sustainable and transparent manner by adopting a societal and economic perspective in underground construction.*

The aim is hence to facilitate societally more profitable decisions on the implementation of risk-mitigation in underground construction by helping decision-makers to identify what risks that need to be prioritized and what measures that best mitigate these risks when facing complex and uncertain decision situations. This is conducted by applying the risk management process (ISO, 2018) on leakage induced risks and by developing the process of identification of risks, the quantification of risk, and the evaluation of risks by increasing the visibility of economic, social and environmental consequences of both leakage induced risks and the implementation of risk-mitigation measures. The evaluation process is made by adopting a societal economic perspective. To meet the overall aim, this thesis has the following specific objectives:

1) To develop a framework for the risk management process applied on hydrogeological risks in underground construction (Paper I)
2) To develop a method and exemplify its usage for identifying risks from leakage into an underground construction (Paper III)

3) To develop and present a method and exemplify its usage for translating risks and risk-mitigation measures into relevant cost and benefit items to enable a cost-benefit analysis (CBA) (Paper II and III).
4) To develop and exemplify a model chain for risk analysis and risk evaluation that allows for updating as new information is available (Paper II and IV)
5) To investigate and exemplify how costs and benefits can be monetized for risk analysis and risk evaluation (Paper II and IV)

1.3 Scope

The scope of the thesis is to describe how the risk management process according to ISO can be applied and utilized to deal with hydrogeological risks in underground construction in an efficient, transparent and sustainable manner. The papers presented in this thesis all connect to one or several parts of the risk management process. All papers include case studies (hypothetical or real-world ongoing projects) to demonstrate what the different steps of the risk management process constitute and how relevant information from each step can be retrieved.

1.4 Limitations

This thesis consists of several limitations that should be noticed. The thesis and its appended papers are delimited by the consequence ethical economic perspective and to developing methods for risk-based decision analysis that can have a practical application. The practical application is exemplified by the case studies. The focus has been on method development and to exemplify to illustrate the application of the risk management process for hydrogeological risk management in underground construction and not on carrying out complete case studies with complete data collection and modelling. Further, specific limitations of the appended papers are discussed in each respective paper.

2 Underground construction and the risk management process

In this chapter the theoretical background to the contents of the thesis is presented. The chapter includes descriptions of hydrogeological risks in underground construction, the risk management process according to ISO (2018), and the definition of risk as used in this thesis and appended papers.

2.1 Groundwater and underground construction

Construction below the ground surface and below the groundwater table are often associated with leakages into the construction. To ensure dry working conditions in the facility, the leakage must be diverted which subsequently may result in declining groundwater levels in the surrounding areas. Lowering of groundwater levels may also be necessary in construction projects, e.g. outside excavation shafts in order to ensure secure working conditions and to avoid e.g. destabilization and bottom heave (Cashman et al., 2001). Dewatering of groundwater resources induced by leakage into the underground construction is known from several underground projects around the world, see e.g. (Chae et al., 2008; Kværner et al., 2013; López-Fernández et al., 2012; Mossmark et al., 2017). Groundwater drawdown induced by leakage can affect large areas surrounding the underground facility (Burbey, 2002; Gustafson, 2012). Although groundwater is an abiotic feature, it has the potential to sustain both abiotic systems such as stable ground and biotic systems such as ecosystems both beneath and above the ground and hence resulting in both abiotic and biotic leakage induced risks.

The relationship between leakage and various effects and their consequences can be described by cause-and effect chains. The nature and severity of the consequences of damage are determined by the dynamic interaction between the different components in the cause–effect chains. Consider for example the cause effect chain: damages to buildings caused by subsidence. The cause- and effect chain is first initiated with a leakage of groundwater into the underground facility. The magnitude of the leakage depends on the transmissivity of the surrounding bedrock (consolidated) or soil (unconsolidated), the pressure gradient of the groundwater, and the sealing design of the tunnel. Depending on the size and duration of the leakage, and the conditions of the hydrogeological system, the groundwater levels in the surrounding aquifers may decline. The magnitude of the groundwater level decline depends on the hydraulic properties of the aquifers, the hydraulic boundary conditions of the system and the water balance. As an example, an aquifer can be located next to a river that continuously recharges the aquifer, and a large leakage will not have any significant impact on the groundwater levels. The opposite is true if the aquifer has boundaries across in which no or little water can flow. At such conditions even a small leakage may cause large impacts on the groundwater levels. The magnitude of the groundwater level decline is thus to a higher degree dependent on the conditions in the groundwater system in comparison to the magnitude of the leakage. If the aquifer is overlain by a layer of clay, the pore pressure of the clay may be reduced due to the lowered groundwater pressure in the underlying confined aquifer. Reduction of pore pressure in clay is a slow process, and the speed is mainly dependent on the permeability and thickness of the clay and hydraulic gradients between the clay and the underlying aquifer. The duration of the decline of groundwater levels is thus decisive for the change of pore pressure in the clay. The lowered pore pressure can initiate a process of subsidence of the ground surface as well as a compaction of the clay. Whether it is initiated or not depends on the historical consolidation of the clay which controls the consolidation properties of the clay. The subsidence can subsequently lead to damage to objects such as buildings, pipes and other installations. The magnitude of the damage depends on the sensitivity of the objects of risk. As an example, the foundation of a building may or may not be sensitive to subsidence depending on the type of foundation and the distribution of the subsidence in the area of the building. If the building gets damaged, consequences of social, environmental, and economic character may arise. Examples of such consequences are the inconvenience for the residentials in the damaged buildings, the environmental footprint of producing new materials to repair the damage on the building, and the investment cost for refurbishment of the building.

As there are many factors controlling the cause-and effect chain of leakage to damage and damage cost, there will always be uncertainties regarding what risks that are present and the quantity of these risks. These uncertainties are a result of the aleatory and epistemic uncertainty that are present in nature (see section 3.8 for a more detailed description of uncertainty). Since the cause-and effect chains of leakage to damage is always uncertain there is not possible to know with certainty what can happen and the consequences if it happens. However, it is relevant to assess the probability of an event happening and the consequences of that event.

2.2 The risk management process

The inherent uncertainty of nature and underground construction calls for a structured approach to assess and manage probabilities, consequences and thus risks. According to ISO (2018), the risk process of managing any type of risk includes the following steps (Figure 2):

- Consultation and communication: Includes all activities that aim at increasing the understanding of the present risks within the project and among stakeholders.

- Establish the context: Defining the aim of risk management as well as defining criteria for the analysis. For the application presented in this thesis, this step constitutes defining the purpose as an evaluation of risk-mitigation measures based on societal economic valuation of costs and benefits where the alternative with the highest net present value is implemented. This step also includes defining the boundary conditions of the risk management process, e.g., legal restrictions on what measures that can be implemented.

- Risk assessment

    - Risk identification: Inventory and identification of risk objects and objects at risk. Risk objects are the underground facility or the activity that causes the risk. The object at risk is the receiver of the risk such as groundwater dependent ecosystems or buildings that are affected by the leakage and the subsequent groundwater drawdown. This thesis proposes the usage of cascades for identification of risks (see section 3.3).

    - Risk analysis: A detailed consideration of uncertainties, risk sources, consequences, likelihood, events, scenarios, controls and their effectiveness.

Often a quantification of risks. The causes and sources of risks can e.g., be described through a cause- and effect chain. The risk level for the identified risks is determined in a quantitative, semi-quantitative or qualitative manner, depending on the circumstances (see section 3.5).

- Risk evaluation: Evaluation based on the aim and criteria defined early in the risk-management process. The purpose of this process is to identify which risks need treatment and which risks need to be prioritized for treatment implementation. The risk evaluation is performed with cost-benefit analysis (CBA) (see section 0)

- Risk treatment: Selecting and implementing options for addressing risk.

- Monitoring & review: Improving the quality and effectiveness of the process by e.g., collecting data to update decision models.

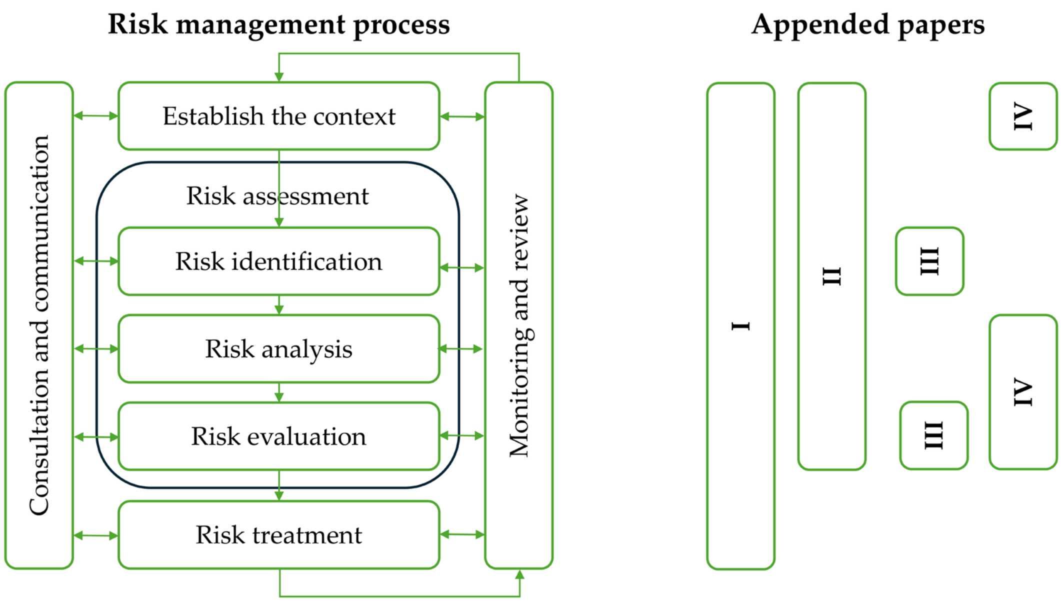

Figure 2. to the left, the risk management process (ISO, 2018) and to the right, indication of the connection of the appended papers to the risk management process different parts.

2.3 Risk definition

There are several definitions of risk. One commonly used definition was presented by Kaplan et al. (1981) where risk is defined as the combination of the probability for an undesired event to happen and the consequences of that event. The risk is defined by the questions:

- What can happen?
- How likely is it to happen?
- What are the consequences if it happens?

In ISO, risk is instead defined as the effect of uncertainty on objectives (ISO, 2018). Given the economic perspective adopted in this thesis and appended papers, risk is here defined as a function of probability and economic consequence, i.e. the expected value of economic consequences of failure to reach a goal. The total risk to society R_{tot} associated with a risk-mitigation measure $i=0 \ldots n$ is

$$R_{tot_i} = E[K_{F_i}] = \int_0^1 K_{F_i}(P_{F_i})dP, \tag{1}$$

where P_F is the probability of an undesired event (failure, F) occurring, and K_F is the economic consequences of that event, i.e., its costs to society. The expected cost setting of Equation (1) is commonly used in practice in CBA (Boardman et al., 2018). However, people's preferences with respect to the probabilities in P_F are typically not considered. In contrast, an option price setting *sensu* (Freeman et al., 2014) is more appealing from an economic theory point of view (Boardman et al., 2018), but is more empirically challenging to apply, requiring more detailed information on people's preferences (see section 3.6 for more detailed discussion).

As illustrated by Figure 3, the risk function includes events with both high-probability–low-consequence risks (illustrated to the left in the graphs) and low-probability–high-consequence risks (illustrated to the right in the graphs). To calculate the total risk, all possible (imaginable) events must be included in the risk analysis. However, in practice, it is difficult or often not feasible to describe all these events. The calculation of risk is in this thesis conducted using a probabilistic approach accounting for uncertainties regarding both the probability of failure and the consequences of that failure (Bedford et al., 2001).

In calculations of risk where consequences constitute damage costs to buildings, the continuous function can be simplified by defining a staircase function where each step represents a damage category, e.g., esthetical damages, functional damages, and stability damages (Sundell et al., 2019; Wikby et al., 2024). The graph in Figure 3a illustrates the risk at a time when uncertainties are large, and when risk-reducing measures have not yet been implemented. Figure 3b illustrates how uncertainty decreases when new information is collected. The total risk is the same as in Figure 3a but the uncertainty regarding the probabilities and the consequences have decreased (see the dashed line). In Figure 3c, a risk-mitigation measure has been implemented with a reduced risk for high-consequence events and a reduced total risk as a result. Taking the example of damages to buildings, Figure 3c represents a situation where a risk-reducing measure, e.g., extra sealing measures to reduce leakage, has resulted in lower probabilities for all consequence (damage cost) categories due to fewer buildings in each consequence category.

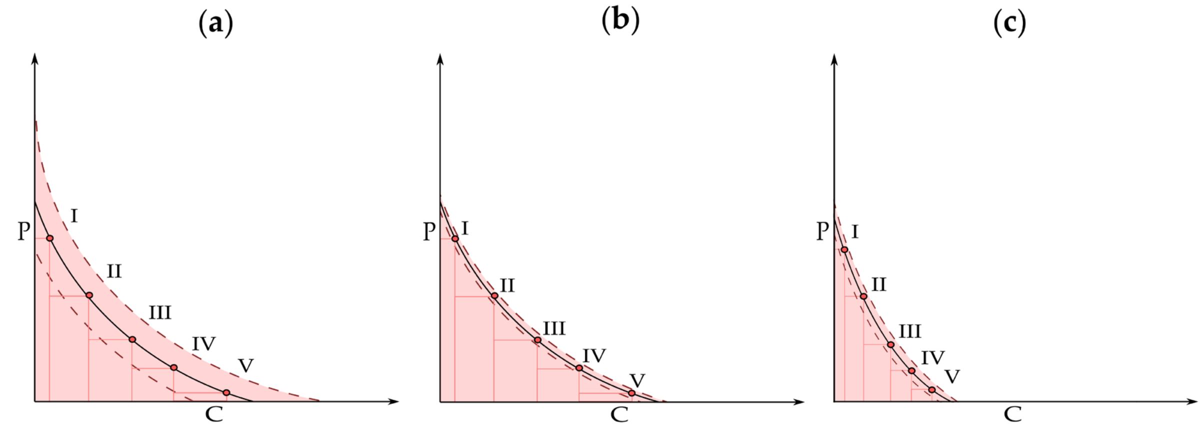

Figure 3. Schematic description of staircase and continuous risk functions indicated by red circles and black solid lines together with an interval for uncertainty indicated by dashed lines. “P” and “C” indicate probability and consequence, respectively. (a) the risk curve in an early stage before any risk-mitigation measures have been implemented; (b) the risk curve after retrieval of more information resulting in less uncertainty, and (c) the risk curve after implementation of risk-mitigation measures resulting in reduced total risk. The figure was published in Paper I (Merisalu et al., 2021).

3 Methods

This chapter includes a description of the underlying methods and techniques used in the papers presented in this thesis.

3.1 Case study applications

Three case studies are featured in the appended papers: (1) Förbifart Stockholm – the northern section of the E4 by-pass road tunnel in Stockholm, (2) Västlänken – Station Haga, a rail tunnel in Gothenburg, and (3) Ostlänken – the Kolmården tunnel, a rail tunnel near Norrköping. Each case study area is located in Sweden and has a hydrogeological setting shaped by deglaciation processes. While the hydrogeological settings share similarities, each site presents different characteristics.

In Stockholm, the underground facilities are constructed mainly in crystalline bedrock, which is overlain by glacial till forming a lower aquifer, and by subsidence-prone glacial clay. An upper, unconfined aquifer is present in sandy soils and filling material near the ground surface. Gothenburg's geological setting is similar, although the clay deposits are generally thicker than those in Stockholm. Also, the glaciomarine clays in Gothenburg are in general more sensitive to land subsidence due to the longer periods with more extensive deposition in a glaciomarine setting. In Norrköping, the lower confined aquifer consists of a larger glaciofluvial deposit above a till layer, and a watercourse running through the area has created a ravine by erosion into the overlying clay, cutting down into the glaciofluvial material.

Although these sites have comparable hydrogeological settings, the objects at risk differ. Förbifart Stockholm and Västlänken both traverse urban areas, but Västlänken passes through the densely populated city center of Gothenburg, whereas Förbifart Stockholm crosses a less urbanized area. In Norrköping, the tunnel runs through a rural landscape, with only a few buildings situated nearby. Here, natural assets such as wetlands and watercourses are the primary objects at risk, whereas in Stockholm and Gothenburg, subsidence-prone buildings and infrastructure are most vulnerable.

3.2 The observational method

The observational method, as outlined by Eurocode 7, is a structured and adaptive method for managing changing conditions as an underground construction project progresses (1997-1, 2004; Peck, 1969; Powderham, 2002). In essence, it reflects a philosophy of "design as you go," using real-time observations to refine both the understanding of site conditions and the needed engineering response. The method includes identification, confirmation or rejection of the most probable site conditions together with the possibility to adapt the design of risk-mitigation measures based on information from investigations. The most probable conditions constitute the basis for the initial design, but a course of action should be at hand for any deviation that can be reasonably anticipated or foreseen. An important part of the observational method, is to decide on relevant and observable control parameters that are representative for the hydrogeological conditions (Holmberg et al., 2007).

The observational method is in line with the hydrogeological risk-management framework presented in Paper I. In the framework, the principles of the observational method constitute monitoring and review. Monitoring and review are essential parts as it provides new knowledge and can detect changes that are necessary to consider. The key principles of monitoring (observing) and reviewing (confirming or rejecting) form the basis for the updating of the models included in the risk analysis and risk evaluation and for the definition of relevant risk-mitigation measures.

In Paper IV, the principles of the observational method constitute the model structure for the cost-effectiveness analysis (CEA) of risk-mitigation measures. The model is set up in such a way that new knowledge regarding the hydrogeological parameters relevant for decisions on risk-mitigation strategy is retrieved as the tunnel progresses. In more detail, the sampling of hydraulic conductivity is conducted in the front of the tunnel as the project progresses and what sealing strategy to adopt is based on the sample values.

3.3 The cascade model

The contributions that ecosystems (i.e., living systems) make to human well-being constitute ecosystem services (Costanza et al., 2017; Haines-Young et al., 2018). There are several frameworks that enable a structured assessment of ecosystem services such as The Economics of Ecosystems and Biodiversity (TEEB) (TEEB, 2010), and the more recent Common International Classification of Ecosystem Services (CICES) (Haines-Young et al., 2018). Other frameworks that supplement CICES include geosystem services (Fox et al., 2020; Lundin Frisk et al., 2022; Van Ree et al., 2016), and water system services (Gärtner et al., 2022). The cascade model is a cornerstone of the CICES framework and is broadly accepted, recognized, and applied in ecosystem services research in Europe (Anzaldua et al., 2018; Kaval, 2019). The model describes how changes in the natural (pre)conditions can result in a changed provision of ecosystem services and subsequent consequences for human wellbeing.

In Paper III, the principles and structure of the cascade model were used to identify societal risks associated with groundwater leakage and to evaluate the benefits of reducing these risks. The cascade model, as applied, is divided into two parts: 1) the hydrogeological system (both the abiotic and biotic parts), and 2) the social and economic systems (Figure 4). The properties and functions of the hydrogeological system enable services which can be translated into benefits through human action. As an example, the hydrogeological system provides the service of opportunities for drinking water extraction but this service is only realized as a benefit once a well is drilled and operating (Fisher et al., 2009).

When groundwater leakage to an underground construction occurs, the properties of the system may change *(Δ)*. The properties identified as relevant to consider and at risk of change due to leakage are: decreased pressure head, decreased saturated thickness, reduced baseflow in recipient, increased unsaturated zone, changed gradient, changed groundwater chemistry, and changed water chemistry in recipient. Changed properties can in turn generate cascades that change the functions which put the services and benefits provided at risk (see equation (1)). Implementing a risk-mitigation measure may limit these changes and thus reduce the risk. The change (reduction) in risk *(Δ Risk)* constitutes the benefits gained from the risk-mitigation measure (see equation (2)).

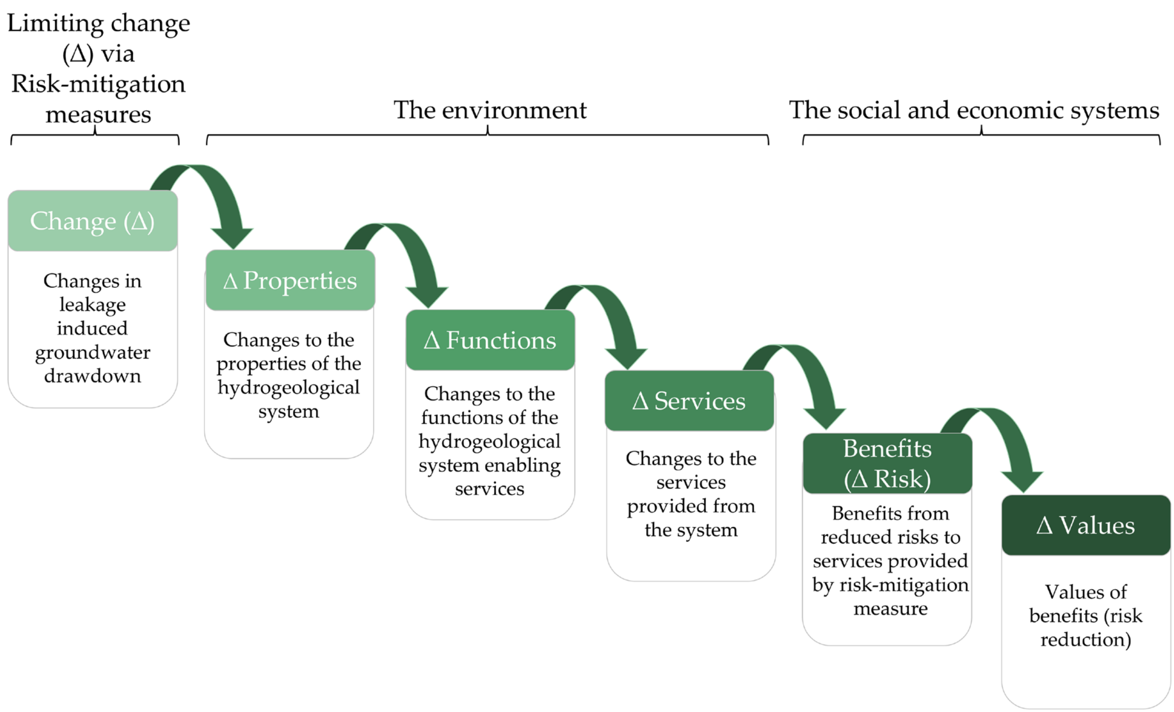

Figure 4. Conceptualization of linkages between limiting/reducing changes (Δ) in properties, functions, and services of the hydrogeological system and the reduced groundwater leakage induced risks, i.e., a benefit (Δ Risk) which has an economic value. Modified from Haines-Young et al. (2018). The figure is published in paper III (Merisalu et al., 2025).

Despite its practical usability in real-world projects, the cascade model is often criticized for having limitations that need to be considered (e.g., La Notte et al. (2019) and Costanza et al. (2017)). A limitation often mentioned is that causal relationship between the levels in the cascade is unidirectional, whereas in reality there might be feedback loops between the different levels of the model. In fact, the cascades that are presented in Paper III do not constitute linear models that can only go from one starting condition (property) to a final value. Instead, some of the cascades can initiate feedback loops that initiate new cascades. Additionally, common criticism is that the cascade model is lacking in mediating the complex, non-linear, and dynamic connections in the ecological systems, i.e. it cannot fully capture the complexity of nature. However, although nature is more complex than can easily be described with a model, the cascade models boxes may capture complexity if the user of the model is able to integrate the full knowledge of the system. Thus, the model itself is not the limitation, the user of the model sets the level of complexity. The cascade model also implies that humans and the social and economic systems are separate from nature, even though humans as biological creatures are part of nature. The anthropocentric view of the cascade model and the concept of ecosystem services in general thus exclude intrinsic values of nature by only focusing on its instrumental value to human wellbeing (Bennett et al., 2015; Haines-Young et al., 2010; McCauley, 2006; Redford et al., 2009). While this is indeed a limitation, dismissing the concept of ecosystem services as a whole should not be the solution. Instead, complementary analysis can be added (Summers et al., 2012). An example of such additions can be to apply a combination of values-centered approaches for valuation that is fair to people and nature including inter- and intrageneration equity (Brondizio et al., 2019; Pascual et al., 2023).

3.4 Cost-benefit analysis and cost-effectiveness analysis

Cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) constitute the basis for decision analysis methods in this thesis. In Paper I, CBA is the main method used for risk evaluation as part of the framework for hydrogeological risk management. In paper II, CBA is used to evaluate the risk-mitigation strategies in the case study of Förbifart Stockholm by quantifying costs and benefits. In Paper III, relevant cost and benefit items are identified for the evaluation of risk-mitigation measures for the case study Ostlänken – the Kolmården tunnel and Västlänken – Station Haga. The cost and benefit items are part of the qualitative CBA set up for the case studies. In Paper IV, quantification of cost-items for evaluation of risk-mitigation strategies is carried out to demonstrate how a CEA can be set up in an early phase of a project.

CBA is a systematic and quantitative method used to evaluate the profitability of projects, policies, or decisions economically by comparing their associated positive (i.e., benefits) and negative (i.e., costs) consequences for human wellbeing for both present and future generations (Boardman et al., 2018; Griffin, 1998; Johansson et al., 2016). Rooted in welfare economics, CBA provides a framework for assessing whether the total benefits of a project including a full life-cycle assessment outweigh its total costs, thereby informing decision-makers about the net present value (NPV) it generates for society. From a normative point of view, CBA implements the Kaldor-Hicks criterion for determining the relative profitability of different projects (Acland, 2022). Costs and benefits are quantified relative to a reference alternative. The fundamental principle of CBA is to express all relevant costs and benefits in monetary terms , enabling a common metric for comparison. This includes both direct market impacts and indirect or non-market effects, such as environmental externalities or social outcomes. A CBA should include all current and future benefits and costs of implementing a measure, both those which are taken into account by the project owner (internal benefits and costs) and those which are not (externalities) (Boardman et al., 2018; Kotchen, 2010). By discounting future costs and benefits to their present values, CBA also accounts for the time value of money, which is essential for long-term planning and investment analysis. Consequences are monetized, i.e., expressed in monetary units, whenever this is judged to be reasonable given available data (Figure 5). The consequences that cannot be expressed in monetary units must as far as possible be described qualitatively and their potential effects on the overall result must be evaluated (STA, 2024).

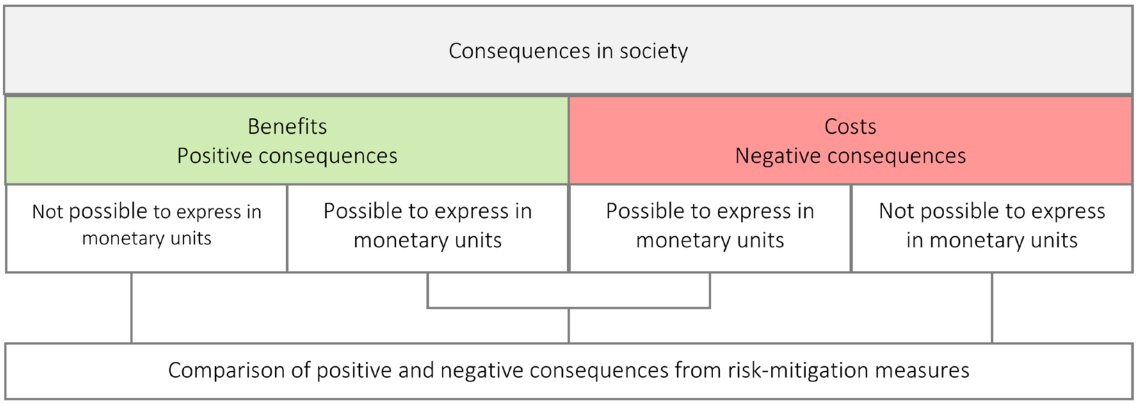

Figure 5. The evaluation procedure of positive and negative effects from risk-mitigation measures. The effects possible to express in monetary units are evaluated using cost–benefit analysis. The effects that are not possible to express in monetary units are described qualitatively. The figure is a modification and is published in Paper I (Merisalu et al., 2021).

In CBA of a risk-mitigation measure *i*, the associated reduction in risk expectancy (see equation (1)), in comparison to a reference alternative, noted with a subindex *ref*, constitutes the benefits of that measure. The reference alternative is often defined as the null alternative, i.e., not implementing any measure (*i*=0), but also other reference alternatives can be relevant. The benefits, *B*, of implementing a measure *i* are thus:

$$B_i = R_{tot_{ref}} - R_{tot_i}, \tag{2}$$

The total expected measure cost, M_{tot}, associated with implementing and operating a risk-mitigation measure, *i*, is:

$$M_{tot_i} = E[L_{M_i}] = \int_0^1 L_{M_i}(P_{M_i})dP, \tag{3}$$

where P_M is the probability that the cost event of a measure will occur, *M*, and L_M is the economic consequences of that event, measured here as the costs to society of implementing and operating the measure. The total measure cost, M_{toti}, is the expected value of the consequences, $E[L_M]$, considering scenarios for all included events and their associated probabilities.

In a CBA of implementing and operating a risk-mitigation measure, the associated increase in expected costs in comparison to the reference alternative constitutes the cost of that measure. The costs, *C*, of implementing and operating a measure, *i,* are thus:

$$C_i = M_{tot_i} - M_{tot_{ref}}, \tag{4}$$

The net present value (NPV_i) of implementing and operating a risk-mitigation measure, *i*, is equal to the associated benefits minus the costs:

$$NPV_i = \sum_{t=0}^{T} \frac{1}{(1+r)^t}[B_{i,t}] - \sum_{t=0}^{T} \frac{1}{(1+r)^t}[C_{i,t}], \tag{5}$$

where T is the time horizon including years t (t=0…T, where 0 denotes the beginning of the first year), $B_{i,t}$ is the benefits during year t of implementing and operating the measure i, $C_{i,t}$ is the costs during year t of implementing and operating the measure i, and r is the discount rate.

CBA typically adopts a utilitarian perspective, in which all benefits and costs are aggregated and treated equally, irrespective of who in society experiences them. As a result, potentially important distributional effects may remain obscured, particularly when a project or policy affects social groups in unequal ways. For example, children may be more sensitive to air pollution than adults, implying that the same environmental impact can have different welfare consequences for different groups. One way to address such differences is to complement the CBA with an equity analysis, which examines how benefits and costs are distributed across society. According to Martens (2011), an equity analysis should address three key questions: (1) which costs and benefits are relevant from an equity perspective, (2) how individuals should be grouped, and (3) what constitutes a fair or equitable distribution. The answers to these questions are context-specific and depend on the nature of the project under assessment. In many cases, a distributional analysis can provide important input to the first two questions by disaggregating benefits and costs across relevant societal groups (Martens, 2009). Income groups are commonly used for this purpose, but other classifications may be equally or more relevant depending on the impacts considered. The information obtained through such a distributional analysis can then serve as a basis for assessing whether the project outcome can reasonably be regarded as equitable. It may also help identify potential win–win opportunities, where measures can be designed to improve outcomes for disadvantaged groups without reducing overall net benefits (Cecot, 2023). In addition, equity has an intergenerational dimension, which in the context of CBA is primarily addressed through the choice of discount rate and its influence on the net present value of long-term costs and benefits.

CBA applies discounting, i.e., to apply a discount rate in the calculation of net present value in order to account for the fact that different consequences may occur at different times (cf. Equation 5). There are mainly two approaches for discounting: the descriptive (positive) approach and the prescriptive (normative) approach (Groom et al., 2022). The descriptive approach bases the discount rate on how people behave justifying the usage of market interest rates from capital markets. The prescriptive approach instead argues that capital markets are not perfect and therefore unsafe to use. With this approach the discount rate is instead based on ethical principles of e.g., not favoring present generations over future ones. The discount rate can significantly influence the result of a CBA both regarding the *NPV* and the ranking of the alternatives (Söderqvist et al., 2015). What discount rate to choose depends on the values and principles within the framework in which the CBA is performed. The Swedish Transport Administration recommends a discount rate of 3.5 % for economic calculations within the field of transport. This value is based on studies of market interests and productivity in the society (STA, 2025). The so-called Stern Review (Stern, 2006) recommends a discount rate of 1.4 % for economic calculations of climate effects and measures against climate change implying a relatively strong recognition of inter-generational equity. Low, and sometimes falling rates over time are sometimes recommended when moral aspects of future generations are considered or when there are large uncertainties regarding the future conditions. An example of falling or changing discount rate over time are the recommendations in the UK where a fixed rate of 3.5 % should be used the first 30 years and after that 3.0, 2.5, and 2.0 % for the next coming 30 year periods (Treasury, 2022). It can be beneficial to calculate the *NPV* with several discount rate in order to analyze how sensitive the *NPV* is to a changing discount rate (Johansson et al., 2016). In paper II, three different discount rates were used: 0, 1.4 and 3.5 %, where the second and third constitute the recommendations from the Stern Review and STA (2025) respectively. In Paper IV, two different discount rates were used: 2.0 % and 3.5 %. The discount rate of 2.0 % was adopted since it, according to Rennert et al. (2022), reflects empirically observed declines in real risk-free interest rates, it aligns with the central tendency among economists, and is theoretically justified for long-term climate policy analysis as it gives increased weight to future damages. The discount rate of 3.5 % was chosen since this rate is recommended to use by the Swedish Transport Administration (STA, 2025).

In practice, it is rarely feasible to quantify and monetize all identified cost and benefit items. Prioritization is therefore required before proceeding to quantification. Such prioritization can be guided by two complementary considerations. First, items may be prioritized based on their expected contribution to the overall *NPV*, focusing analytical efforts on effects that are likely to be decisive for the outcome of the analysis. This perspective is consistent with standard CBA practice (e.g., Boardman et al. (2018)). Second, prioritization may account for the perceived importance of different impacts among experts or stakeholders. These perspectives can be defined through structured expert-based or participatory methods, such as Delphi studies, Q-methodology, or other systematic ranking and weighting exercises (Brown, 1980; Dalkey et al., 1963; Hsu et al., 2007; Watts et al., 2012).

CEA determines which of several alternative measures that meets a specified target at the lowest cost (STA, 2025), without requiring all benefits to be monetized, which can sometimes be challenging (Reu Junqueira et al., 2023). Unlike CBA, which evaluates whether a project generates net societal value, CEA ranks interventions based on their effectiveness in achieving a specific target. A central methodological insight in CEA is that the ranking of alternatives is not intrinsic to the alternatives themselves but depends on how the target is defined. Different alternatives often deliver different types of benefits, and the choice of target therefore decisively shapes the analytical outcome. With a less ambitious target, low-cost alternatives often emerge as the preferred option. In contrast, a more ambitious target frequently render low-cost alternatives infeasible because they fail in fulfilling the target, while more expensive alternatives may be the only ones capable of fulfilling the target. How the target is formulated will therefore directly influence the result of the analysis and the CEA can then be used to investigate how the preferred alternative changes with different target levels. (Kurth et al., 2024; Reu Junqueira et al., 2023). Concepts such as discounting future costs, and considerations of equity and distributional effects, remain essential in CEA just as they are in CBA.

3.5 Quantification of effects and coupling of models

Quantifying the effects of groundwater leakage is crucial to enable a quantitative risk evaluation. A quantification of effects will often require several coupled models that each one describe the chain of events that constitute the initiated cascade. The choice of approach for different models depends on factors including time and financial resources, data availability, desired level of detail, system complexity, and the context of the particular underground construction project. Models may be data-driven, process-based numerical simulations, extrapolated from sources such as experimental studies, or informed by expert input (Merisalu et al., 2021).

In Paper II, a chain of models was used for risk analysis and risk evaluation of risk-mitigation alternatives (Figure 6). The risk analysis starts with a model of leakage followed by a model for groundwater drawdown induced by the leakage. The third model constitutes pore pressure reduction where the declining groundwater levels were used as input. The result from the pore pressure model was used as input to a subsidence model. Several damage models were developed for the identified objects at risk. All these models describe the relationship between the magnitude of subsidence and the probability of damage. As final models in the risk analysis, cost-models describing the economic cost if damage occur were developed. As a final step the risk expectancy of leakage was simulated for the reference alternative as well as all risk-mitigation alternatives (see equation (1)). The result from the risk analysis was used as input to the risk evaluation. As a first step, the benefits (reduced risk expectancy) were calculated by comparing the difference in risk expectancy of the reference alternative and each risk-mitigation alternative (see equation (2)). The second step was to calculate the measure cost for the different mitigation alternatives (see equation (3)). The next step was to calculate the cost from the measure cost for the reference alternative and each risk-mitigation alternative (see equation (4)). As a final step, the NPV was calculated (see equation (5)).

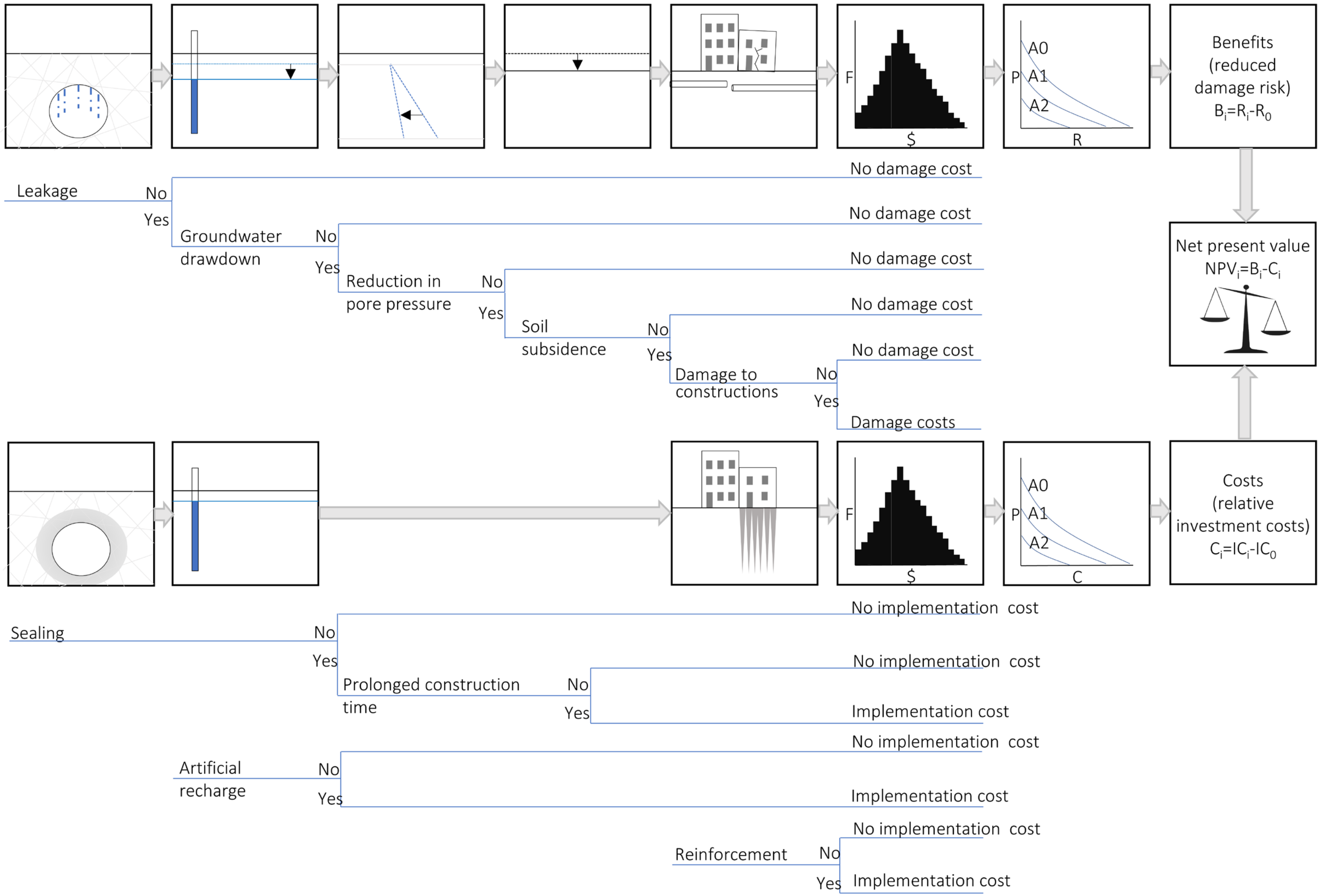

Figure 6. Schematic illustration of the coupled models for evaluation of cost and benefits of risk-mitigation. The upper part of the Fig. illustrates the chain of events (models) used for the simulation of risk expectancy used in the risk analysis. The lower part illustrates the chain of events (models) used for the simulation of implementation cost. The last column of the figure illustrates the risk evaluation where the benefits and costs are compared for all defined risk-mitigation alternatives. The figure is included in Paper II (Merisalu et al., 2023).

3.6 Monetization

If possible, costs and benefits should be expressed in monetary terms. A wide range of valuation methods are available for both market and non-market goods, and for capturing use as well as non-use values. The choice of method for each identified consequence depends on the nature of the impact, data availability, and the feasibility of collecting new data (Freeman et al., 2014). In some cases, multiple valuation methods may be required to capture different components of a single risk. For impacts traded on markets, observed market prices can often be used as proxies for economic value. For example, physical damage to a building can be partly valued using repair costs. However, such costs may not fully reflect the total welfare loss incurred by affected individuals. Property damage may also give rise to stress, discomfort, and disruption, which constitute real costs to society but for which market prices are typically unavailable. These welfare effects should therefore, whenever possible, be identified and included in the analysis, either quantitatively or qualitatively.

One way to assign value to different consequences is by applying standard values relevant to the specific context, such as those of the Swedish ASEK system (STA, 2025), which guides investment decisions in the transport sector. When appropriate standard values are unavailable, estimates from existing studies, like those found in the Environmental Valuation Reference Inventory (EVRI) or the Ecosystem Services Valuation Database (Brander et al., 2021) can be adopted through benefit transfer methods (Boutwell et al., 2013; Boyle et al., 1992; Johnston et al., 2021). Primary valuation methods are also available. There are two main groups of primary valuation methods: revealed preference (RP) and stated preference (SP). The first one, the RP methods, estimates the value individuals place on goods or services based on their actual behavior on a related market, while the SP methods are instead based on hypothetical market behavior by using surveys to pose questions to individuals e.g., regarding their willingness to pay for a non-market good. The SP method can be used to obtain information on both use and non-use values.

In risk-based decision analysis, monetization is frequently performed using an expected damage approach, where benefits of mitigation measures are quantified as reductions in expected damage costs *ex post*. This approach is widely applied in practice due to its transparency and relatively modest data requirements (Boardman et al., 2018). However, expected damage costs may differ from the total economic value of risk reduction, particularly when damage estimates are limited to direct repair costs. Important welfare impacts, such as stress and anxiety associated with exposure to risk, may then be omitted, and individual preferences regarding risk reduction as such may not be fully reflected. While more comprehensive *ex ante* valuation approaches, such as option pricing based on willingness to pay for risk-mitigation measures (risk reduction), can in principle address these issues, empirical estimates are often unavailable or difficult to obtain for the specific risk contexts considered in applied CBAs. Given these practical limitations, the expected damage approach remains a reasonable and commonly used approximation. A key requirement when applying this approach is therefore to explicitly identify all relevant consequences, and to acknowledge the potential for underestimation of the total economic value of risk reduction.

In Paper II, monetization was limited to market-price-based methods. Cost estimates were derived from project documentation, comparable projects, and expert elicitation, and complemented with cost data from external sources, such as records of pipe breakage obtained from the municipality of Gothenburg. In Paper IV, all cost estimates were obtained through structured expert elicitation, where domain experts compiled and assessed cost data for the variables of interest based on experience from similar projects. These applications reflect the pragmatic balance between methodological rigor and data availability that characterizes monetization in risk-based decision analysis for underground construction.

3.7 Expert elicitation and Bayes' theorem

Existing data samples may be too small, too unreliable, too costly to obtain, or even unobtainable and thus insufficient to support the risk assessments (Paté-Cornell, 2012; Sjöstrand et al., 2020) If this is the case, the only option for collecting data may be to elicit information from experts (O'Hagan, 2019). The purpose of the expert elicitation is to retrieve knowledge regarding an uncertain variable's quantity. The uncertainty is preferably represented by probability density functions (Jenkinson, 2005). Expert elicitation was used in Paper I and in Paper IV. Expert elicitation adopts a Bayesian approach by treating expert judgments as subjective probability distributions. In this context, subjectivity is not seen as a flaw but as a quantifiable input. Experts' beliefs are thus formalized into prior distributions, which can then be updated with observed data. Bayes' theorem provides the mathematical foundation for this updating process. It states that the posterior probability of a hypothesis is proportional to the prior probability multiplied by the likelihood of the observed data (Gelman et al., 1995). This allows for a coherent integration of prior beliefs and empirical evidence, resulting in updated distributions that reflect both sources of information. In practice, this means that expert-derived priors can be refined as new measurements or observations become available, improving the reliability of probabilistic models over time. The Bayesian framework is particularly valuable in settings where data are sparse or uncertain, as it enables transparent and iterative learning (Stefan et al., 2022). Moreover, it facilitates decision-making under uncertainty by quantifying how beliefs change in response to evidence.

In Paper II, the expert elicitation was conducted in three steps. First, workshops were conducted where experts involved in the tunnel project discussed challenges, defined the context, and identified relevant risk-mitigation strategies. The second step was data collection where the experts compiled project-specific and external data, including groundwater levels, leakage, subsidence, damage reimbursement costs, mitigation costs (e.g., sealing, artificial recharge), forecasts for unfinished tunnel sections, delays, and cost data from similar projects. The third step constituted interviews where the experts participated in face-to-face interviews to develop damage and cost models. Individual experts provided best estimates with uncertainty intervals, while groups reached consensus on most likely, minimum, and maximum values. For a few variables, point estimates were used instead of distributions.

In Paper IV, the expert elicitation was conducted using the SHELF-framework which is a structured approach for conducting expert elicitation (Gosling, 2018; O'Hagan, 2019; Oakley et al., 2007). The SHELF method can be summarized into five main steps. Step 1 is the preparation where the goals and parameters to be elicitated are defined, experts are selected and briefed, and background information and relevant data are collected and complied. The second step is the elicitation session(s) that may constitute workshops or interviews. In Paper IV, two workshops were conducted. In the sessions, each expert was asked to provide a best estimate (median) of the variable, lower and upper bounds, as well as a uncertainty interval (quartiles). The third step constitutes the facilitated discussion where the expert together discusses their reasoning and data. The aim here is to reach consensus and if not possible, document differing views. The fourth step is the aggregation where the experts' judgements are combined into a single distribution. This step can be achieved in two ways: 1) through mathematical aggregation (e.g., averaging, and 2) behavioral aggregation, thus reaching group consensus. In Paper IV, both types were used. The fifth and last step is documentation which is significant to ensure transparency and reproducibility. In Paper IV, all elicitations workshops were video recorded to make sure that the discussions and reasoning were well documented.

3.8 Modeling with uncertainty

Since it is impossible to describe the reality in full detail, models are often used to predict future behaviors given certain conditions. According to Walker et al. (2003) the uncertainty of model-based decision support can be distinguished as three dimensions of uncertainty, the location of uncertainty, the level of uncertainty, and the nature of uncertainty.

The location of uncertainty describes where uncertainty appears within the model complex. The locations for uncertainty are context, model, inputs, parameters, and model outcome. Context includes uncertainties regarding the boundaries of the model and thus the economic, environmental, political, social, and technological situation that forms the context for the problem being examined. Uncertainty in context can also arise from ambiguity in problem framing and differences in stakeholder perspectives, which makes it important to consider alternative framings and validate the chosen context. Model uncertainty constitutes uncertainties regarding both the lack of understanding of the system and the ability of the model to represent the system. This includes uncertainty about the structure of the model such as which variables, relationships, and assumptions are included as well as technical uncertainties that may arise from software or hardware implementation, like coding errors or algorithmic flaws. These uncertainties can only be reduced by an improved understanding of the system and by updating the conceptual, physical, or mathematical model. Models are always simplifications of reality, both because inherent uncertainty makes it impossible to describe reality exactly and because simplifications are often made deliberately to make the model usable, for example with regard to computation time (Burgman, 2005; Sturk, 1998). Input uncertainties concern the description of the current (reference) system and the forces influencing it. This includes uncertainty about external driving forces, such as scenario and policy variables, as well as uncertainty in the system data used to quantify features and behaviors of the reference system. Parameter uncertainty is uncertainty about the constants used in the model, which can arise from limitations in data or calibration methods. Different types of parameters such as exact, fixed, a priori chosen, and calibrated may each contribute to the overall uncertainty, especially when calibration data are insufficient or not fully informative.

The level of uncertainty describes the degree to which knowledge about the system or model is limited. It can be divided into statistical uncertainty, scenario uncertainty, recognized ignorance, and total ignorance. Statistical uncertainty refers to uncertainty that can be described and handled using statistical methods, such as probability distributions or measurement errors. Scenario uncertainty arises when there are several plausible ways the system could develop, but it is not possible to assign probabilities to these outcomes; this is often addressed through scenario analysis. Recognized ignorance means there is a fundamental lack of knowledge about the mechanisms or relationships being studied, making it impossible to even construct meaningful scenarios. Total ignorance represents the deepest level of uncertainty, where not only are the mechanisms and scenarios unknown, but there is also no awareness of what is not known.

The nature of uncertainty can be divided into two categories: 1) aleatory uncertainty, which arises from nature's inherent variability, and 2) epistemic uncertainty, which stems from our lack of knowledge about the system (Aven, 2012). Aleatory uncertainty (also called variability uncertainty) is due to the natural randomness or heterogeneity in systems, such as the spatial variation of geological properties like fracture zones. This type of uncertainty is considered irreducible, as it cannot be eliminated by collecting more data. In contrast, epistemic uncertainty (or knowledge uncertainty) results from incomplete understanding or limited information about the system. It can often be reduced by gathering more data or improving models for example, increasing confidence in estimates of geological heterogeneity through additional drilling or field tests. However, practical constraints such as cost or feasibility often limit the extent to which epistemic uncertainty can be reduced, meaning that decisions must frequently be made with limited information. In many cases, both types of uncertainty may be present, and distinguishing between them is important for choosing appropriate strategies for uncertainty management.

Uncertainties must be accounted for, and models that are accessible and transparent for both policy makers and stakeholders should be the aim (Saltelli et al., 2014). There are mainly two approaches used for handling the uncertainty in underground projects: the deterministic approach and the stochastic approach (Sturk, 1998). The deterministic approach is the most traditional. The deterministic approach uses data from measurements, and properties at unsampled locations are often determined by interpolating the data. The deterministic approach usually deals with uncertainty by adding a safety margin or a factor of safety (Alén, 1998; Freeze et al., 1990). There are two major criticisms to this approach: first, the regionalized variables (or variables of interest) can vary irregularly in space and can thus not be determined by interpolation; second, values at unsampled locations are subject to uncertainty (Dagan, 1982). Within this work (Paper II and Paper IV), uncertainties were mainly accounted for by stochastic modeling with input variables constituting probability density functions. The stochastic approach or the reliability approach uses probability theory to quantify the uncertain parameters within a model. It is however also recommended (see e.g., Draper (1995) and Zhang (2021)) to evaluate structural uncertainty connected to the choice of model. However, this has not been carried out for the work presented herein. Stochastic models aim at giving predictions for all possible outcomes and to assess the probability of these. If an input parameter to a model is associated with uncertainty and is specified as having a distribution of probability, then the analysis requires a stochastic approach that can generate a result with a distribution of probability (Bedford et al., 2001; Freeze et al., 1990). The uncertainty analysis is carried out by representing all input variables with probability distributions and by running the model with Monte Carlo simulations (Figure 7). Monte Carlo simulations facilitate many iterations; thus, the result is calculated many times. For each calculation, a random value from each input distribution is drawn resulting in quantification of the uncertainty of the output variable.

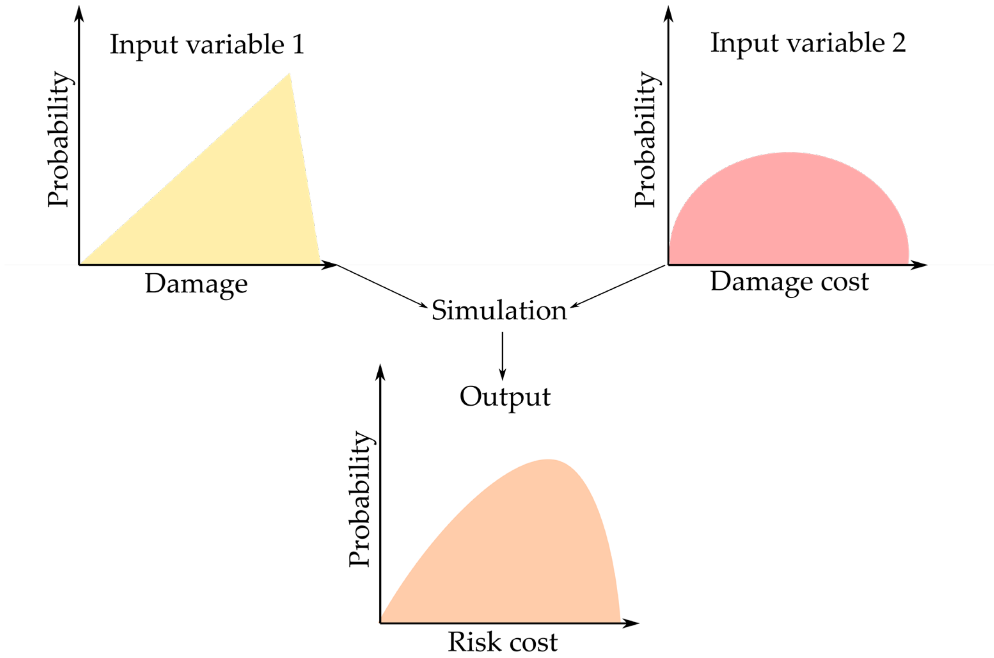

Figure 7. Principle description of stochastic simulation where uncertainties in the input variables result in uncertainties in the output. The figure is published in Paper I (Merisalu et al., 2021).

3.9 Sensitivity analysis

A sensitivity analysis is an important part of a risk management process (Burgman, 2005). It is a method used to determine how changes in input variables affect the output of a model or system. It helps identify which inputs are most influential, and how uncertainty or variation in those inputs impacts the results (Saltelli et al., 2006). A common method for sensitivity analysis when using Monte Carlo simulations is to quantify correlations between the input and output variables (Hamby, 1994). If relationships in the model are linear and variables normally distributed, Pearson correlation is typically used. If the model is non-linear, Spearman rank correlation can instead be used (Iman et al., 1979). In Paper I, a more detailed review on different techniques of sensitivity analysis is described. In Paper II, two sensitivity analysis were conducted, one for the subsidence calculations and the risk expectancy, and one for remaining input parameters to the CBA. The argument for dividing the sensitivity analysis into two parts was the difference in the number of dimensions used in the two models where the subsidence is simulated spatially in two dimensions whereas the CBA conducted in the paper only uses one dimension. Spearman rank correlation coefficient was used for both, this since all variables are not normally distributed. In Paper IV, two sensitivity analysis were also conducted, again the Spearman rank correlation coefficient was used.

4 Summary of appended papers

In this section, the four papers appended in this thesis are summarized.

4.1 Paper I

Merisalu et al. (2021) presents a framework for managing hydrogeological risks in underground construction. It includes a comprehensive description of the challenges associated with decisions on hydrogeological risk-mitigation in underground construction together with commonly used approaches and methods for handling these challenges. The main result of the paper constitutes the presented novel framework for probabilistic risk-based decision analysis for decision support on the mitigation of hydrogeological risks in underground constructions where the presented methods are combined and incorporated for a sustainable and economically efficient risk management process. The framework uses the ISO standard framework (ISO, 2018) as a point of departure. The developed framework handles the complex nature of environmental impact in the surroundings of the facility as well as the evaluation of risk-mitigation measures. Furthermore, the framework accounts for the inevitable and changing uncertainties associated with underground constructions by incorporating an iterative process of continuous updating of the risk analysis and the risk evaluation models as new information is retrieved.

The framework, as illustrated in Figure 8, starts with defining the scope and criteria for the project. The next step is to identify all possible risks that leakage into underground construction may give rise to. Once all risks have been identified, risk-mitigation measure alternatives relevant for preventing or reducing the identified risks are defined. The total risk is in a next step estimated by means of data, models, simulations, an expert elicitation, for all defined risk-mitigation measure alternatives. This is followed by the risk evaluation, which by means of CBA evaluates the positive and negative consequences of the risk-mitigation measure alternatives. To evaluate what input parameters to the model that has the largest impact on the result, a sensitivity analysis is carried out. In the following step, the CBA may be updated by means of Value of Information Analysis (VOIA) in order to evaluate whether to implement a risk-mitigation measure alternative or collect more data and thus postpone the decision on implementing a measure. A VOIA is a CBA that compares the cost of collecting more data (information) to the reduced risk of making an erroneous decision on the choice of what risk-mitigation measure alternative to implement. In a VOIA, additional information is only valuable if it changes the preferred decision. Thus, from a strict economic perspective, the collection of more data should only be carried out if the retrieved information is more valuable than the cost of collecting it (Freeze et al., 1992; Zetterlund et al., 2015). Whatever decision is made, more data is continuously collected and processed and used to update the models. This loop of risk analysis, risk evaluation, decision making, and monitoring will continue throughout the project allowing for continuous updating of the models and thus enabling updated decision-support.

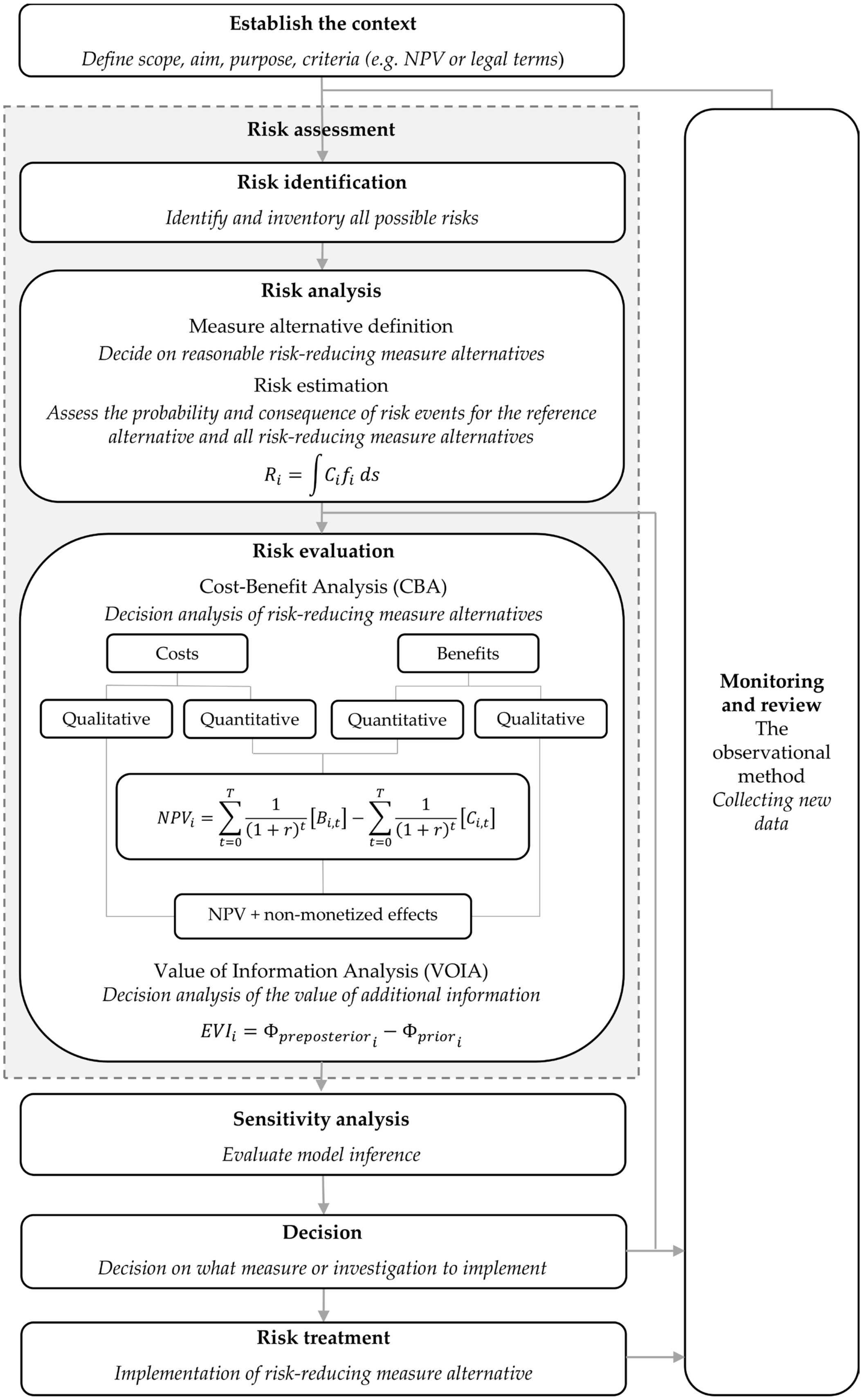

Figure 8. The hydrogeological risk-management framework for decision support on risk-mitigation measure alternatives. The figure is included in Paper I (Merisalu et al., 2021).

4.2 Paper II

In Merisalu et al. (2023), the framework presented in Merisalu et al. (2021) is applied on a case study. The case study constitutes a road tunnel within the Förbifart Stockholm project located in Stockholm, Sweden. The main scope of the study was to provide support to decision makers in the tunnel-project on decisions on hydrogeological risk-mitigation measures. For this purpose, five risk-mitigation measure alternatives (including one reference alternative) were evaluated (Table 1). The alternatives are all based on different combinations of sealing-, artificial recharge-, and reinforcement strategies. Two sealing strategies were considered relevant for this study. The first sealing strategy (Original) is based on the original sealing strategy specified by the project owner in the planning phase of the project. The second sealing strategy (Modified) constitutes a sealing design assessed necessary to fulfill the leakage criterion in the legal permit. The first sealing strategy was based on the accumulated knowledge of the hydrogeological conditions in the bedrock from the planning phase of the project, before excavation started in 2018. The modified strategy was based on knowledge regarding the conditions that were revealed during excavation and thus constituted the accumulated knowledge from the planning phase and the excavation phase until the autumn 2019 when this study was conducted. The artificial recharge is divided into no recharge or recharge necessary to counteract groundwater drawdown. One alternative did also include reinforcement measures on subsidence sensitive buildings.

Table 1. Risk mitigation alternatives.

Mitigation alternative	Sealing strategy	Recharge strategy	Fulfills leakage requirements	Cause damage
0	Original	No recharge	No	Yes
1	Modified	No recharge	Yes	Yes
2	Original	Recharge	No	No
3	Modified	Recharge	Yes	No
4	Original	No recharge	No	Yes*

* No damages to subsidence sensitive buildings

The cost (implementation and operation costs) and benefits (here reduced damage risks) were evaluated using coupled models for the risk analysis and the risk-evaluation as described in section 3.5. The costs, benefits and the NPV for the discount rates 0, 1.4 and 3.5% are presented for the 5th, 50th and 95th percentiles in Figure 9. The benefits are highest for alternatives 2 and 3 (median value around 165 MSEK). This is due to the artificial recharge in both these alternatives that maintain stable groundwater levels subsequently resulting in no subsidence damage. The choice of discount rate does not have a large impact on the benefits indicating that the subsidence occurs shortly (within a few years) after the initiated groundwater drawdown. This corresponds well with the measurements of subsidence performed continuously as a part of the environmental monitoring program of the project. The investment cost is highest for risk-mitigation measure alternative 3 (median value around 7000 MSEK), followed by alternative 1 (median value around 1700 MSEK), 2 (median value around 660 MSEK) and 4 (median value around 4 MSEK). The discount rate impacts the costs for both alternative 2 and 3 due to the recurring costs for artificial recharge included in both alternative 2 and 3 (*T=120*). The NPV is highest (median value around 0 MSEK) for alternative 4 followed by alternative 2 (median value around -630 MSEK), 1 (median value around -1692 MSEK) and last 3 (median value around 7140 MSEK). It is important to notice that alternative 3, which has the lowest NPV, is the only alternative that fulfills the leakage requirement and causes no damaging impacts.

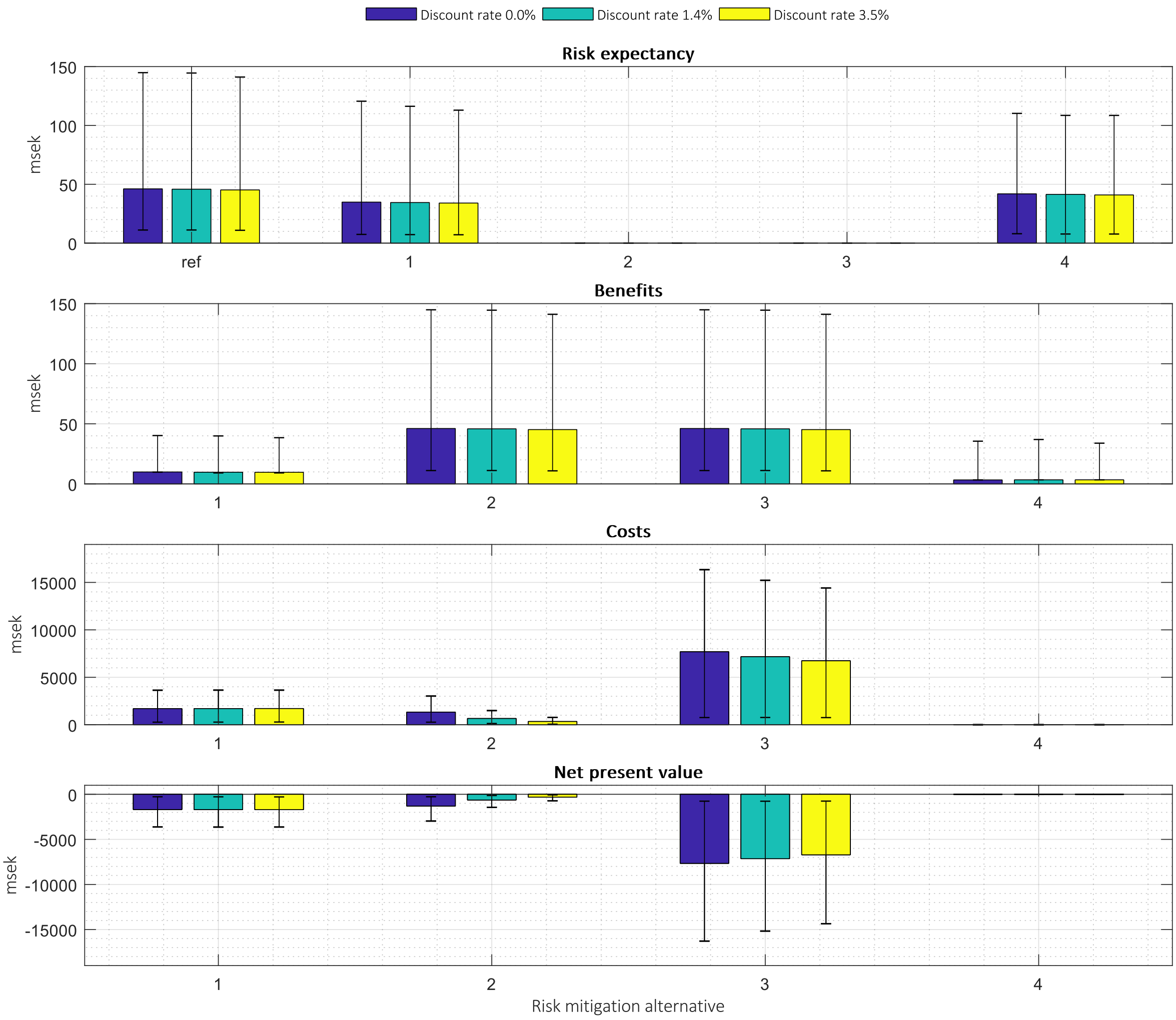

Figure 9. The benefits (a), costs (b) and NPV (c) in million SEK for the risk-reducing measure alternatives 1-4 and for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile. The value given in text represents the 50th percentile. The figure is included in Paper II (Merisalu et al., 2023).

The main conclusions of this study were:

- The usage of expert elicitation in combination with data and empirical models enables the cost-benefit analysis of risk-mitigation measure alternatives when data is limited.

- The CBA in the case study showed that the net benefits in the form of reduced economic damage-risk are small relative to the implementation costs for risk-mitigation measures due to the few objects at risk and the large implementation costs of sealing measures.
- The cost of implementing the risk-mitigation measure alternative 3 that fulfills the legal requirements and prevents damages (7000 MSEK) are not proportional to the benefits obtained (165 MSEK). Thus, the legal requirements drive the costs for the project without proportional societal benefits.

In this study, only reimbursements cost associated with repairment of damage to the built environment were included. However, there are also other sorts of consequences associated with subsidence damage that were not included. To enable a more robust inclusion of consequences for future studies, the next study conducted within the PhD-project focused on developing an approach for a more holistic identification of relevant cost and benefit items that could be included in such analysis.

4.3 Paper III

Merisalu et al. (2025) mainly focuses on the risk identification step of the risk management process as well as the risk evaluation part. Paper III primarily addresses both the process of identifying risks and evaluating them as part of risk management. Because identifying risks is fundamental to effective risk management and understanding the costs and benefits of mitigation measures is essential for conducting a comprehensive CBA, Paper III introduces a method for identifying relevant risks and the corresponding cost and benefit items that serve as inputs for a CBA. It presents a thorough approach for identifying the potential benefits and costs of implementing hydrogeological risk-mitigation strategies. The unique aspect of this approach is its integration of hydrogeological expertise related to common hydrogeological settings with the cascade model, which is a widely recognized framework for connecting natural, social, and economic systems (Haines-Young et al., 2018). By categorizing risks triggered by groundwater leakage and systematically identifying the benefits of addressing these risks, this method provides a structured way to account for the full chain of impacts, from groundwater impact to broader societal and economic outcomes. Paper III also presents general forms of relevant leakage-induced cascades, supplemented with literature examples, offering a tool for identifying risks that consider all stages from groundwater impact to social and economic consequences. By integrating the cascade model framework with knowledge from international literature, this approach offers a universal method adaptable to a range of hydrogeological settings.

In Figure 10, one of the cascades from Paper III, the cascade of the change in the property pressure head, is presented. The figure describes that a decrease in pressure head (property) in confined aquifer can give rise to pore pressure reduction in overlying soft soils and thus increase the effective stress (function). This can in turn result in instability of the soil (subsidence) and thus decreased access to stable ground (service). This may in turn result in the risk of damage to the built environment which subsequently may lead to the need for reparation and other subsequent risks. The subsidence may also initiate a new cascade constituting changes to natural water system (property) which in turn can decrease drainage (function) and decrease transportation of excess water (service). This may in turn result in the risk of expansion of flood risk areas which may also result in the need to repair damage and other subsequent risks. In Paper III, other cascades constituting impact on other properties of the hydrogeological system are presented.

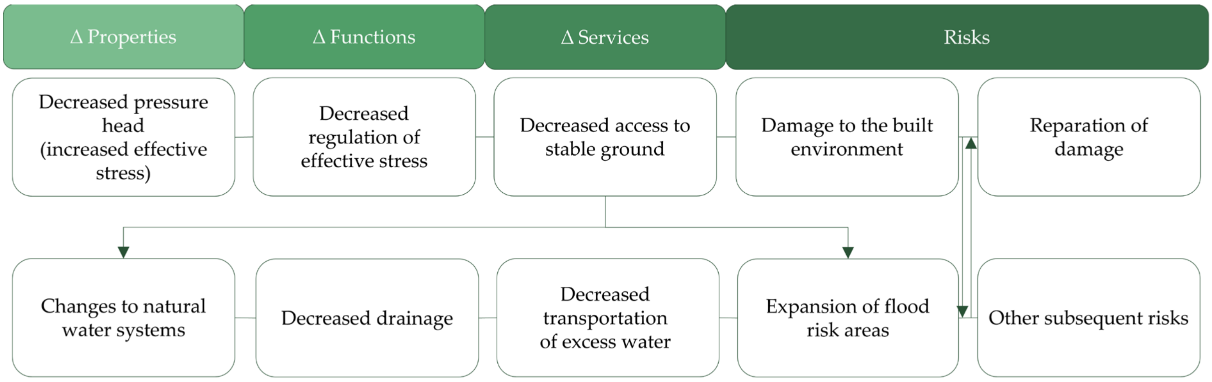

Figure 10. Identified subsidence risks triggered by decreased pressure head and decreased access to a stable platform to build upon/within. The cascade should be read from left to right and top to bottom. Arrows are present to highlight exceptions regarding direction or simply to guide the reader. The figure is included in Paper III (Merisalu et al., 2025).

In Table 2, the risks identified in the cascade of decreased pressure head are translated into potential benefit items of implementing risk-mitigation measures aiming at reducing the change to the properties, functions and services for the case study Västlänken - Station Haga. The table indicates that the risk of e.g., damage to the built environment and the risk of needing reparation can result in several economic consequences to be valued in a CBA. These consequences constitute costs for traffic relays due to the reparation work, investment in labor and material for reparation, emissions from manufacturing the material used for the reparation, emissions from machinery used for the reparation, transport of material and equipment used for the reparation, lost revenues for businesses due to reparation work, increased noise due to reparation, and inconvenience for residents due to reparation work. There are also other risks associated with damage to the built environment that may result in economic consequences that's needs to be valued in a CBA. Such consequences constitute damages that cannot be repaired (e.g., damage to historical buildings), stress due to concerns among residents or property owners, water shortage due to pipe bursts, sewer leakage due to pipe bursts and contamination of groundwater, traffic delays due to damage on roads and rails (e.g., increased travel time, increased emissions, and increased risk of accidents), increased maintenance, and decreased attractiveness of the area and reduced property value. This translation of risks into consequence items to be valued constitute parts of a qualitative CBA. If quantified and monetized, a quantitative CBA can be conducted.

Table 2. Identified primary and secondary risks due to decreased pressure head in the lower confined aquifers for the case study Västlänken Station Haga translated into economic consequence items (K_F in Equation (1)) that may occur because of the risk events. The expected value of the consequences ($R_{tot\ i}$ in Equation (1)) is obtained by associating probabilities of failure (P_F in Equation (1)) with the consequences. Avoidance or reduction of risks from $R_{tot\ ref}$ to $R_{tot\ i}$ thanks to the implementation of risk-mitigation measures constitutes benefit items (B_i) in a CBA (see Equation (2)). The Table is included in the Supplementary material of Paper III (Merisalu et al., 2025).

Primary risk event	**Secondary risk event**	**Economic consequence items (K_F) to be valued for the CBA**
Damages to the built environment	Reparation of damages	Traffic delays due to reparation work (e.g., increased travel time, increased emissions, and increased risk of accidents).
		Investment in labor and material for reparation
		Emissions from manufacturing materials used for the reparation
		Emissions from machinery used for the reparation work
		Transport of material and equipment used for the reparation
		Lost revenues for businesses due to reparation work
		Increased noise due to reparation
		Inconvenience for residents due to reparation work
	Other subsequent risks	Damages that cannot be repaired (e.g., damage to historical buildings)
		Stress due to concerns among residents or property owners
		Water shortage due to pipe bursts
		Sewer leakage due to pipe bursts and contamination of groundwater
		Traffic delays due to damage to roads and rails (e.g., increased travel time, increased emissions, and increased risk of accidents)
		Increased maintenance
		Decreased attractiveness of the area and reduced property value

Paper III also outlines a framework for identifying relevant cost items to be valued in a CBA in more detail compared to previous papers. The focus here is both the implementation cost of measures, both project internal and external, as well as e.g., maintenance costs. Paper III also highlights the project risks associated with implementing measures that need to be considered on the cost side of a CBA. Examples of such project risks are the failure of the measure to meet the objective and thus the need to implement more measures. The delay of project delivery due to failure in implementing measures may also constitute a major item in the CBA. Here, the postponed opening of the facility may cause substantial costs through the postponement of benefits gained from the facility. Not meeting legal requirements may also result in several costs for the project e.g., the cost of the supervisory authority to stop production and thus induce a delay.

The main conclusions of Paper III were:

- The cascade model helps to identify hydrogeological risks from groundwater leakage in underground projects.
- Comprehensive cost lists ensure that all risk-mitigation expenses are covered in the CBA.
- Case studies show that the model applies to both rural and urban environments.

- Combining risk cascades, cost lists, and local knowledge facilitates a comprehensive CBA.
- The qualitative CBA demonstrates how risks and costs can be turned into specific benefits and expenses, guiding quantitative analysis and avoiding double counting.
- Given the significant economic impacts of groundwater leakage, structured CBA of mitigation alternatives is essential for efficient resource use.

The more detailed description of cost items relevant to include in a CBA forms the outline for the next paper which focuses on quantifying costs associated with leakage management in an early phase of a project.

4.4 Paper IV

The fourth paper appended in this thesis focuses on CEA to evaluate risk-mitigation measures alternatives for leakage management in an early phase of an underground project, using a Bayesian approach and expert elicitation to quantify uncertain variables. The model is demonstrated on the Kolmården tunnel (Ostlänken railway project, Sweden). The model presented in Paper IV adopts the Observational method, which is adaptive and relies on real-time data to decide in risk mitigation implementation as construction progresses. Decisions are updated as new information becomes available, reflecting a "design as you go" philosophy. Several sealing strategies are analyzed (pre-grouting, post-grouting, drained and undrained linings), combined with different legal and functional requirements for groundwater leakage. In total, seven risk-mitigation alternatives are evaluated, reflecting combinations of sealing strategies and legal requirements (Table 3).

Table 3. The alternatives analyzed in this study all constitute a combination of risk-mitigation strategy and scenarios.

Risk-mitigation alternative	**Scenario**	**Sealing strategy**	**Description**
0	A	0	The project has leakage requirements of 1.6 l/min in each 20-meter section. No sealing measure will be implemented.
1	A	I	The project has leakage requirements of 1.6 l/min in each 20-meter section. Pre-grouting will be implemented.
2	A	II	The project has leakage requirements of 1.6 l/min in each 20-meter section. Pre-grouting and post-grouting will be implemented.
3	B	II	The project has leakage requirements of 1.6 l/min in each 20-meter section. If the project fails to fulfill the requirements it will apply for a new permit. Pre-grouting and post-grouting will be implemented.
4	B	III	The project has leakage requirements of 1.6 l/min in each 20-meter section. If the project fails in fulfilling the requirements it will apply for a new permit. Pre-grouting, post-grouting and drained lining will be implemented.
5	C	III	The project has measure implementation plan to fulfill a function requirement of leakage into the operational part of the tunnel of <1.6 l/min in each 20-meter section. Pre-grouting, post-grouting and drained lining will be implemented.
6	A	IV	The project has leakage requirements of 1.6 l/min in each 20-meter section. Pre-grouting, post-grouting, and undrained lining will be implemented.

The tunnel is divided into sections, each classified into one of three rock classes with different hydraulic conductivities and thus different needs regarding sealing measures. Probabilistic distributions are used to simulate the occurrence and properties of these classes. The model simulates progress in construction by moving through all sections of the tunnel for every iteration (Figure 11). The distribution of rock classes in the 397 sections is the first part of the model. The next step in the model was to assign a value for hydraulic conductivity for each section to enable the calculations of leakage and decisions on risk-mitigation measure implementation.

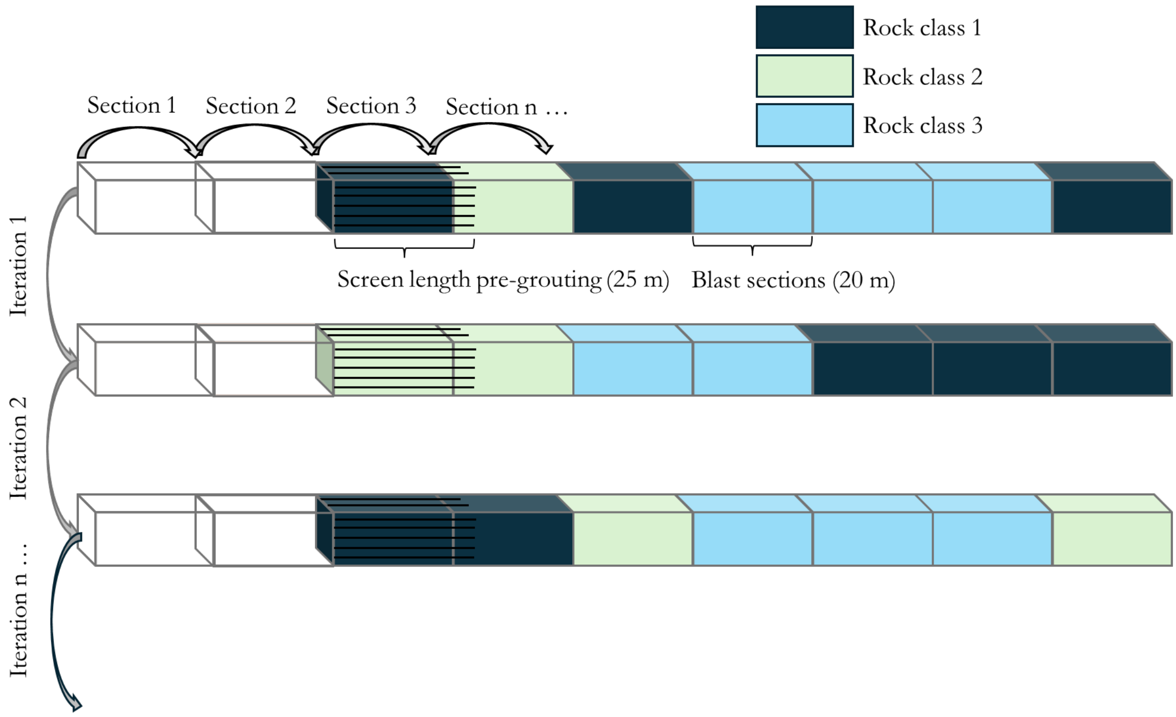

Figure 11. Schematic illustration on the model setup where the tunnel is divided into 20-meter sections where each section represents a rock class (1, 2 and 3 constituting fractured crystalline rock with a low hydraulic conductivity, deformation zones with anticipated higher hydraulic conductivity, and weaker and more permeable crystalline rock in the ravine, respectively. The model moves through all sections of the tunnel for each iteration.

What pre-grouting design that is chosen depends on the hydraulic conductivity for the section measures with water pressure tests in five boreholes in the tunnel front and the leakage requirements set for that section. If the hydraulic conductivity is < $2x10^{-8}$ m/s then no pre-grouting will be carried out. If the hydraulic conductivity is >$2x10^{-8}$ m/s and <$2x10^{-7}$ m/s then grouting design 1 will be carried out. If the hydraulic conductivity is > $2x10^{-7}$ m/s then grouting design 2 with more fine-grained cement is implemented (Figure 12). Post grouting will be carried out in sections where the leakage of groundwater is unsatisfying even after pre-grouting. If the groundwater leakage is >1.6 l/min and in a 20-meter section, then post-grouting will be carried out in that section. If the leakage of groundwater is still >1.6 l/min and in a 20-meter section after post-grouting, then a concrete lining will be implemented. The final step of the model was to calculate the costs for the alternatives using cost variables quantified from expert elicitation.

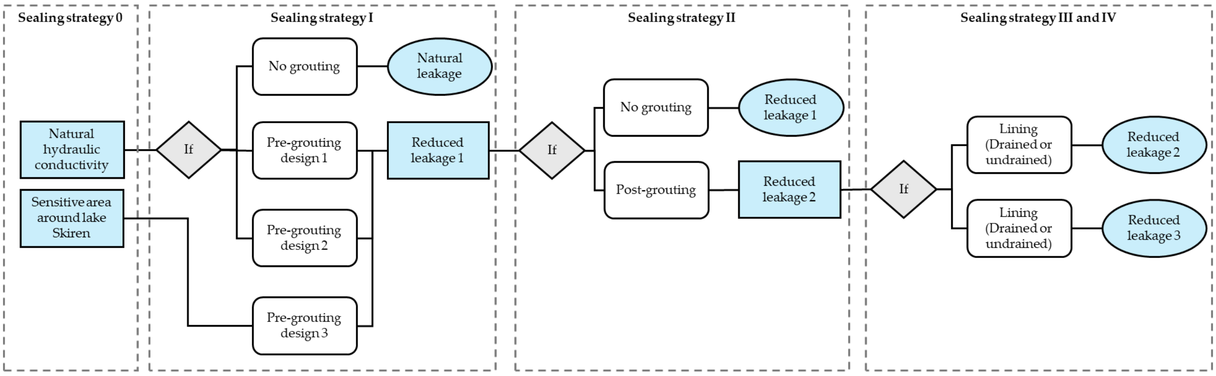

Figure 12. An event tree describing the model setup for evaluation of leakage for the different risk-mitigation measure alternatives. The event tree describes the model setup for one section of the tunnel constituting 20 meters but the same model is used for all sections of the tunnel for all iterations.

The total costs for managing groundwater leakage at a 2.0% discount rate and SCC1 are shown in Figure 13. The left plot presents the project's internal costs. Alternatives 1, 2, 5, and 6 differ only slightly because pre-grouting accounts for most leakage reduction, while post-grouting and linings are applied only in limited sections. Alternatives 3 and 4 show a potentially large cost increase due to the risk of needing a new permit if any section fails the leakage requirement. Thus, the scenario assumptions strongly affect the results. If the project has legal leakage requirements (Scenarios A and B), it is more cost-effective to install an undrained lining and meet the requirements than to stop after post-grouting and apply for a new permit. In Scenario C, where the requirement concerns implementing measures, the project can meet both regulatory and functional demands by installing drained lining in a few sections. It should be noted that the model assumes construction stops during a permit application, making delays the main cost driver. In practice, construction often continues during the application period, and whether work is halted depends on the supervisory authority, an uncertainty not included in the model. The central plot shows external costs, i.e., CO_2 emissions associated with the measures. Since all alternatives depend mainly on pre-grouting, emissions are nearly equal across alternatives. However, the risk-mitigation alternatives show negative values in some iterations. These arise because costs are calculated relative to the reference alternative: negative values indicate that CO_2 emissions in the reference case are higher. The reference alternative includes no sealing strategy (Strategy 0), thus emissions stem only from water collection and dispersion.

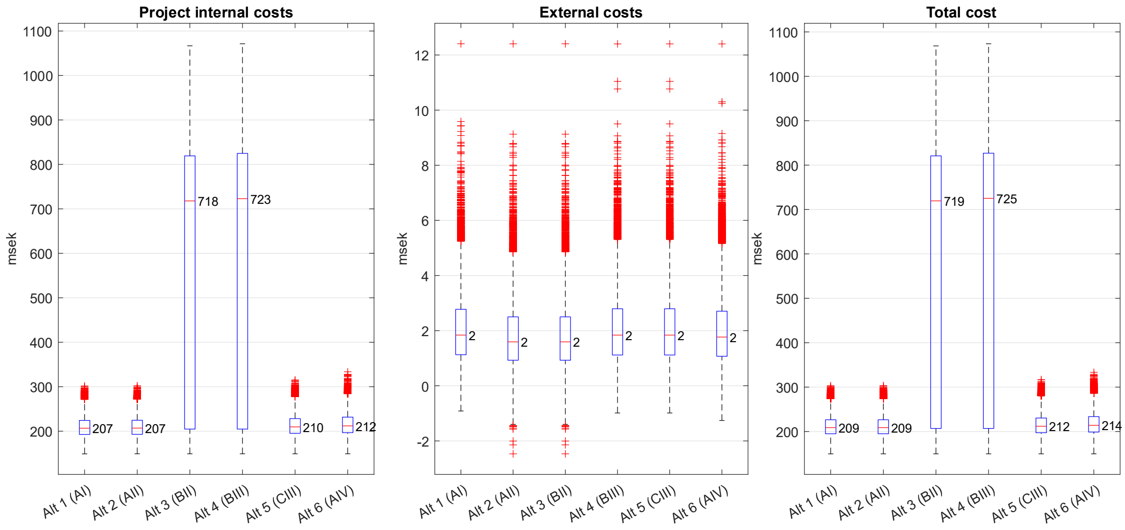

Figure 13. These three subplots describe the costs for the different risk-mitigation alternatives analyzed for the discount rate of 2.0 % and the *SCC_1*. The plot on the left presents the project internal costs for leakage management including both the implementation of measures and application for a new permit. The central plot indicates the external costs associated with leakage management. These costs include the social cost for CO_2 emissions. The plot on the right shows the total cost of water management thus the combined cost from the left and central plot.

The main conclusions of this Paper IV were:

- Project internal costs in the Kolmårds tunnel are dominated by delays and potential permit applications, not by the direct costs of sealing or water management. Thus, the legal framework strongly affects both costs and strategy: requirements based on leakage limits versus required measures lead to different optimal risk-mitigation choices.
- A decision-support model based on the observational method and Bayesian updating allows early evaluation of risk-mitigation options and legal requirements when data is scarce, and can be refined as new information becomes available.
- The quantified cost variables for sealing a double-track tunnel in crystalline rock can be reused in similar projects, but must be updated if key conditions differ (e.g., tunnel size or hydrogeological conditions).
- CEA enables comparison of risk-mitigation measures without valuing benefits directly, but the choice of target is critical: less ambitious targets favor low-cost options, while more ambitious targets can render them insufficient.

5 Discussion

In this chapter the content of the work herein presented is discussed. Strengths and weaknesses of the methods, tools used, and results are presented along with implications and recommendations regarding practical application of methods for implementation of the hydrogeological risk management framework.

5.1 The iterative process and coupling of models

The hydrogeological risk management framework presented in this thesis constitutes an iterative process that requires updating of models to be relevant after new information/data is collected. This means that all models included in the risk assessment (risk identification, risk analysis and risk evaluation) must be constructed in such a way that they are easy to update with new information. Since it is often necessary to couple several models, they must be constructed in such a way that an update in one of them progresses easily through the model chain. Practically, this means that it could constitute a challenge to develop models in different software where data output from one model must be manually handled to be able to use as input to the next model. It could also be a challenge if different parties/companies are responsible for different parts of the model chain. This places considerable demands on the project manager responsible for integrating the collective efforts of all contributors into the final product and for making sure that the whole chain, from risk identification to risk evaluation, is always up to date.

In Paper II and IV, the models and their generated results represent the level of knowledge at the point in time when the study was conducted. In Paper II, the project was in phase when the original sealing strategy had failed to fulfill the leakage requirements, and a new risk-mitigation design was to be adopted. The project continued and the tunnel progressed. However, the case study was not continued, and the models were thus not updated as new data was collected. Hence, the results in the paper are only representative of that moment in time when the study was conducted. In Paper IV, the project was in a phase where the construction of the tunnel had not yet started. The field investigations were also limited. This means that the models created for this case study, and their results are based on limited pre-excavation data. New data regarding e.g., hydraulic conductivity of the main fracture zones and bedrock, could change the result. However, risk assessment, including the risk evaluation can always only be based on the available information including both hard (e.g., samples) and soft data (e.g., expert judgement). The key is to use the available information and be transparent of the uncertainties.

5.2 A white box

When the internal logic of a model is hidden and the model simply relates to input and outputs without being transparent regarding the internal assumptions, processes, or functions, it is often referred to as a black box (Hanea et al., 2022; Maeda et al., 2021). There are several reasons why models developed for the primary objective of decision support in risk management in underground construction should avoid the black box construction and instead be transparent (Reynolds et al., 2014). Examples of such reasons are that transparent models allow stakeholders to understand how decisions are made. This builds trust in the models and their outcomes, especially when decisions have significant consequences. If the decision leads to failure, a transparent model can be used to understand why the decision led to failure and how it could be improved forward. Transparency also ensures that others can reproduce the results, validate the model(s), and assess robustness. In multidisciplinary projects, such as underground construction, transparent models facilitate communication between experts from different fields (e.g., engineers, economists, lawyers, and policymakers), enabling more effective collaboration. The use of probabilistic modelling also promotes transparency of uncertainties. By applying probability density functions to uncertain variables, the models are more honest regarding the lack of knowledge and the underlain conditions that underground projects inevitably are associated with. With that said, developing all models in a transparent manner will make the hydrogeological risk management framework presented in this thesis into a white box that is highly useful for decisions on risk-mitigation measures. In complex and expensive projects such as underground construction projects where the project budget is large and the cost of erroneous decisions are potentially large, it is motivated to spend resources on risk management and thus decision models. As a final remark on transparency, the uses of different software and interfaces entails that assumptions and settings are well documented. This could be an administrative burden that could easily be avoided by building models as scripts that are easy to attach to any report or publication.

5.3 Boundary conditions of the risk management process

Environmental legislation and legal permits for groundwater extraction in underground projects will form boundary conditions for the risk management process. Thus, decisions on what risk-mitigation measure to implement must follow the legal requirements for the specific project. Practically, this means that any risk-mitigation alternative can be evaluated but decisions on implementation can only be applied to those alternatives that fulfill the requirements. Hence, applying a risk-based decision analysis after any legally bounding requirements are set results in a more constrained analysis. However, one solution to this could be to perform the analysis before any requirements are set and use the result from the evaluation as support for decisions on reasonable requirements.

According to Chapter 2, paragraph 7 in the Swedish Environmental Code, when the proportionality principle shall be applied, a measure's ability to prevent or limit damages or inconveniences shall be weighed against the cost for implementing the measure. The cost for fulfilling the rules of consideration in Chapter 2 shall be motivated from an environmental point of view. This means that the balance between the benefits for human health and the environment that comes from implementing the measure and the resulting implementation cost must not be unreasonable (Swedish Government Bill 1997/98:45, part 2, p.24–25). The same Bill also states that it is the project owner's responsibility to show that the cost for implementing a measure is unreasonable or unmotivated from an environmental point of view. There are two main factors that should be considered for the application of the proportionality principle. The first one is the character of the inconvenience such as the level of danger or the extent. The other one is the sensitivity of the area affected by the project (Swedish Government Bill 1997/98:45, part 2, p.25). For underground constructions in urban environments, the sensitivity of the area can e.g., be dependent on the cultural and economic value of the subsidence sensitive buildings within the area of influence of the tunnel. There is no guidance in the Bill for the environmental code regarding how the proportionality principle should be applied. Therefore, it is up to each court to interpret the law text when applied. According to Söderqvist, et al. (2015), the proportionality principle is often not applied in a structured manner in cases for an environmental permit. When applied, it is not always transparent in the written verdict how it has been applied. The same is true for permit cases for underground construction and thus groundwater diversion (Merisalu et al., 2020).

The hydrogeological risk-management framework presented in this thesis can be applied several times during an underground project's lifespan (Figure 14). First, the framework can be applied to evaluate the risks and possible measures to reduce these risks in the planning phase of the project (t_0), before any legal requirements are set. The result of the analysis can be used as a decision support in the court ruling for both the project owners' suggestions on requirements and the court's ruling of the same. This will provide valuable support to the court to apply the proportionality principle and thus increase their possibility of deciding on reasonable requirements. The aim of the analysis in this step is thus to get familiar with the hydrogeological risks of the project and to generate decision support for legal requirements. In a second step, once the requirements are set (t_1), the models are updated and only risk-mitigation alternatives that fulfill the requirements are evaluated. The aim of the analysis in this step is thus to evaluate what risk-mitigation strategy to apply to manage the risks and to fulfill the requirements. This step should be carried out before the construction phase. It is also possible that a third step is necessary. The third step should be carried out during the construction phase (t_2) if any deviation from the anticipated conditions is discovered. The models are then updated with this new information, and the risk-mitigation alternatives are evaluated based on their capacity to manage these new risks and to fulfill the requirements. This three-step process is of course a simplification of how the risk-management framework should be applied. Preferably, all models constituting the risk assessment are updated continuously as new information becomes available and as soon as any condition changes (e.g., legal requirements are set, or new hydrogeological data is collected). This way, decision makers can always make updated and well-informed decisions.

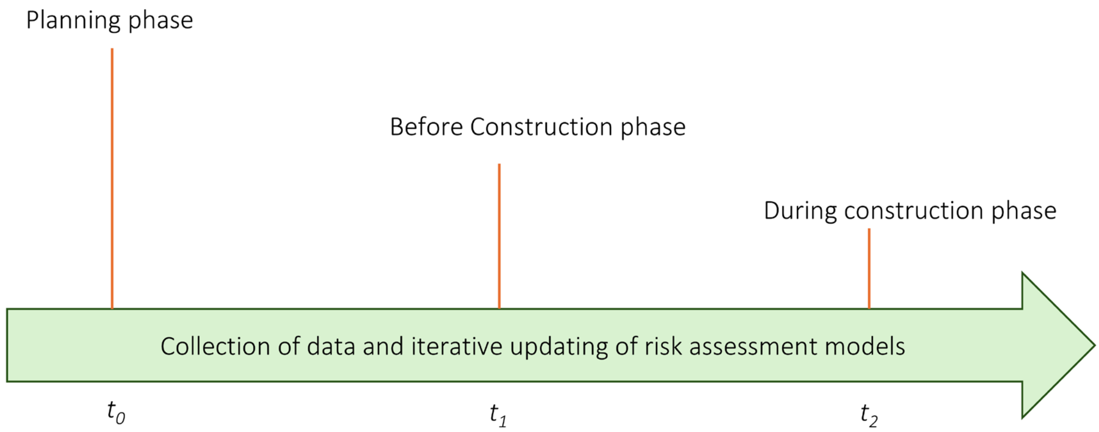

Figure 14. A simplification of a project's phases and the times when decisions on risk-mitigation must be made. The models used for the risk assessment are updated continuously as new data is collected.

5.4 Limitations of CBA and CEA

As mentioned previously in this thesis, CBA adopts utilitarian consequential ethics meaning that it has a human-centered perspective that focuses on human wellbeing where an action or decision is judged on the basis of its contribution to overall utility, i.e. human wellbeing now and in the future (Farley et al., 2020; Imran et al., 2014). In general, the strength of CBA should not be seen as the absolute NPV of an alternative being investigated. Rather, its strength lies in the knowledge-acquiring and knowledge-creating process that the analysis entails, in which a wide range of competencies collaborate to identify, quantify, and value consequences (Söderqvist, 2025). However, many argue that sustainability concerns such as intrinsic and relational values of nature as well as the value of biodiversity loss and socio-environmental justice may be difficult to fully capture, see e.g., Pascual et al. (2023). A similar challenge arises in CEA, which avoids explicit monetization of benefits but still operates within a consequentialist and anthropocentric logic. While this makes CEA attractive in situations where monetization is problematic or ethically contentious, it may also oversimplify complex sustainability dimensions that cannot be meaningfully reduced to a single unit of effect, particularly when ecological, social, or distributive impacts differ qualitatively across alternatives. Moreover, CEA does not inherently resolve concerns related to rights-based values or intrinsic environmental values, as these aspects may fall outside the chosen target.

There are also those who argue against the common belief that CBA and CEA is inherently tied to utilitarianism and incompatible with non-utilitarian moral theories and that methods, e.g., using input and output filters, can be used to allow CBA to respect rights-based moral theories (Lowry et al., 2012). In addition to these adaptations, other decision-support methods can be employed when there is a need to more directly and accurately incorporate aspects such as intrinsic values of nature or rights-based considerations. One such approach is Multi-Criteria Decision Analysis (MCDA), which differs fundamentally from CBA and CEA by allowing multiple criteria, both quantitative and qualitative, to be considered. MCDA enables explicit weighting of diverse objectives, including ecological integrity, cultural significance, and social justice, and often involves stakeholder participation to ensure legitimacy and transparency in trade-offs (Barfod et al., 2011; Donais et al., 2019; Rosén et al., 2015; Saarikoski et al., 2016). MCDA is particularly beneficial in contexts where sustainability concerns are multidimensional and cannot be adequately captured through anthropocentric and consequential ethics, making it a valuable complement rather than a substitute for CBA and CEA (Mouter et al., 2020).

5.5 Decision support models and decisions

According to ISO 31000, decisions about risk treatment should be based on a thorough evaluation of the risk assessment results, considering both the expected benefits and the costs of proposed actions. ISO emphasizes that treatment options may include avoiding the risk, reducing it, sharing it (e.g., through insurance), or accepting it when residual risk is deemed tolerable. The models constituting decision support generated from the risk management framework presented in this work constitute CEA - which yields the probabilistic cost of risk-mitigation alternatives to reaching a defined goal and CBA - which yields probabilistic estimates of net benefits across multiple risk-mitigation options. An essential part of the CEA and the CBA is the risk analysis that quantifies the likelihood of system failures and the expected economic cost of such failures. However, translating probabilistic model output into final decisions is rarely straightforward. While models identify which option that maximizes expected value or minimizes expected loss, choosing among alternatives also depends heavily on decision-makers' risk attitudes and underlying values. What constitutes the "best" option for a risk-neutral individual may be unacceptable for someone who is highly risk-averse or unwilling to tolerate certain types of failure (Fehr-Duda et al., 2012).

Foundational work in decision theory (e.g., von Neumann et al. (1953) and Savage (2012)) demonstrates that individuals do not always make choices aligning with expected utility maximization. These classical theories laid the groundwork for modern decision-support models but also highlight that preferences and beliefs strongly influence choices under uncertainty. This reflects psychological phenomena such as overweighing low-probability events or being loss-averse (Fehr-Duda et al., 2012). On a societal level, risk tolerance is shaped by cultural and psychological factors, as discussed by Slovic (1987), who emphasizes that perceived voluntariness, controllability, and dread strongly influence acceptability. For example, people generally accept relatively high risks associated with driving because it is a voluntary activity. In contrast, risks linked to nuclear power are subject to extremely strict limits. This discrepancy illustrates how societal values and perceptions shape acceptable risk levels: voluntary risks are tolerated higher than involuntary ones (Slovic, 1993). In order to govern acceptable risk thresholds, stakeholders perspectives must be integrated and accounted for in the decision making process (Renn et al., 2016).

5.6 Recommendations

Many decisions regarding hydrogeological risk-mitigation must be taken under uncertainty, often with significant financial consequences. In such contexts, erroneous decisions can lead to considerable and unnecessary costs. The risk-management framework presented in this thesis offers a structured approach to reducing the risk of erroneous decisions by clarifying the economic implications of alternative mitigation strategies. By integrating hydrogeological risk assessments with economic evaluation, the framework can enable practitioners to identify cost-effective measures, avoid unnecessary costs, and thus better allocate resources under uncertainty. When applying the framework in real-world projects, the following recommendations are provided:

- Evaluation of risk-mitigation measures can only be as good as the alternatives selected for evaluation. Thus, what risk-mitigation measures that are evaluated must be carefully selected. It is also important to remember that alternatives can be improved, altered, added or removed several times based on the result from the evaluation in the iterative process of risk management.

- It may be impossible to identify every risk inherent in real-world systems (Kaplan et al., 2001). Consequently, the results of risk assessments are always based on certain assumptions and simplifications. To ensure that these aspects are not neglected during risk management or decision making, it is advisable to explicitly include the excluded risks qualitatively. Thus, the inclusion of known unknowns is important.

- If quantitative data needed to support the risk analysis is lacking, the only sound option may be to elicit information from experts. If that is the case, the elicitation is preferably conducted with a structured method e.g., with the SHELF framework (Gosling, 2018).

- To enable updating of the risk assessment models, it is important to decide on relevant and observable control parameters that are representative of the hydrogeological system and its inherent risks. For example, for decision models on implementation of sealing measures such as grouting, hydrogeological parameters such as hydraulic conductivity or fracture aperture are valuable information to feed the model.

- It is also often impossible, too expensive, or too difficult to quantify all economic consequences (costs and benefits). Thus, prioritization of what items to be valued is necessary.

- A fundamental precondition for effective application of the risk management framework presented in this thesis is the presence of an organization with the competence, resources, and structures required to work systematically with risk. ISO 31000 underlines that risk management should be an integral part of governance, decision-making, organizational culture, and operational processes. Thus, the practical usefulness of the methods developed in this thesis ultimately depends on the ability of the responsible project organization to understand, interpret, and continuously engage with the risk management process as part of its core operations.

6 Conclusions and future research

In this final chapter the main conclusions of this work are presented. Possible further development and application of the methods described is also presented.

6.1 Conclusions

The overall aim of this thesis is to develop methods and present examples of how the well-established risk management process according to ISO can be applied to manage hydrogeological risks in a sustainable and transparent manner in underground construction. The aim is hence to facilitate societally more profitable decisions on the implementation of risk-mitigation in underground construction by helping decision-makers to identify what risks that need to be prioritized and what measures that best mitigate these risks when facing complex and uncertain decision situations. This aim is pursued within a consequentialist ethical framework, where decisions are evaluated based on their consequences for human wellbeing. This thus can support decision-makers in identifying what risks that need to be prioritized and what measures best mitigate these risks under uncertain decision situations given acceptance of this ethical perspective. This can be achieved by strengthening the identification of risks, the quantification of risk, and the evaluation of risks by increasing the visibility of economic, social and environmental consequences. The overall aim and the specific objectives of this thesis have been met in accordance with the following main conclusions:

- The framework for hydrogeological risk-mitigation in underground construction (Paper I) was developed to provide a structure for the risk management process for decisions on implementation of risk-mitigation measures. The framework embraces the whole cause-and effect chain from leakage to damage costs and addresses the spatial difficulties associated with large scale (km^2) groundwater impacts from leakage. It also highlights the time-dynamic conditions with different levels of uncertainty throughout a project and emphasizes the need to build models that allows for iterative updating following the Bayesian statistical approach as well as the observational method as new information/data is retrieved and collected.

- The cascade model, a well-established framework for linking natural, social, and economic systems, was adopted to categorize leakage-induced risks (Paper III). Relevant groundwater leakage-induced cascades were presented in a general format, together with examples from the literature to provide a tool for risk identification that considers the whole chain of events from groundwater impact to social and economic consequences. This results in a general method that is applicable across various hydrogeological settings. The generic arrangement of the presented cascades also enables application as new construction technologies emerge since the initiation of a cascade is not fixed to a certain technology but rather to the effects on the groundwater conditions from the construction activity.

- Both CBA and CEA can be applied to support decisions on hydrogeological risk-mitigation. CBA evaluates whether the societal benefits of a mitigation measure outweigh its societal costs without requiring a predefined target level, which makes it possible to identify what level of protection or regulatory condition is economically justified, even though practical implementation may be constrained by legal requirements. CEA, in contrast, evaluates the cost of achieving a defined target and thereby allows systematic exploration of how cost-effectiveness changes across different targets. Through this, CEA can also provide indirect guidance on what target levels may be reasonable by illustrating the cost implications of alternative targets.

- To enable a CBA or CEA for risk evaluation of risk-mitigation measures, the costs and benefits (in CBA) of these measures must be identified. In Paper II, subsidence risks induced by leakage were identified and the benefits of reducing these risks were monetized. Costs of implementing the risk mitigation alternatives were also monetized. However, in this paper, the number of items that were monetized was limited and the result from this paper reflects this limitation. The limitations constitute the limited number of identified subsidence sensitive objects at risk and valuation that only consider costs for repairment. In Paper III, identified risks, implementation costs, and project risks of risk-mitigation measures were translated into case specific cost and benefit items for two case-studies, and a qualitative CBA was set up. The qualitative CBA indicates what consequences should be monetized to enable a complete quantitative CBA that avoids double counting.

- How to set up a model chain for risk analysis and risk evaluation was demonstrated in Paper II and paper IV. In Paper II, the model chain contains all necessary models needed for risk analysis and risk evaluation. In Paper IV, the models are used for the CEA. In the examples provided in the papers, all models were developed and executed in MATLAB (MathWorks, Natick, MA, USA) enabling a smooth transition of data between the models.

- In both a CEA and a CBA, the items (costs or benefits) must be monetized. In Paper II, only market-price based methods were used for monetization. The input data came from the experts involved in the project and the cost-estimates were based on cost data from the project or other similar projects. Expert elicitation was also used to complement the existing data. Some of the cost-estimates also came from other sources such as cost on pipe breakage that was retrieved from the municipality of Gothenburg's database of such costs. In Paper IV, a comprehensive monetization of implementing risk-mitigation measures was conducted through expert elicitation. In advance, the experts had compiled cost data on the variables of interest from other similar projects.

- The application of the risk management process for decision-making on hydrogeological risk-mitigation measures in underground construction as described in this thesis enables a transparent procedure for decisions that account for both economic, social and environmental consequences. The development of models that are easy to update and where all of the input variables and the model structures are easy to follow also enables both the decision maker but also stakeholders to better understand the result from the risk evaluation. This has been expressed through communication with project leaders in the case studies used in the studies. This increases the change of decisions based on the best possible knowledge and better understanding and communication both within the project organization and to affected parties.

- As a final comment, this thesis demonstrates that there are compelling reasons for the Swedish Transport Administration to further develop and apply risk-based decision analysis for managing hydrogeological risks in underground construction. Several of the principles and methodological approaches already embedded in ASEK (STA, 2025) can be effectively leveraged into the context of underground construction, as illustrated by the examples presented in this work. At the same time, it is important to emphasize that the ultimate design of such an analytical framework, whether based on CBA or CEA, or with the inclusion of weighting or prioritization procedures, must remain the responsibility of the decision-making authority. This dissertation provides theoretical and methodological foundations, complemented by practical examples, to support such development and highlights key considerations for implementing risk-based decision analysis for managing hydrogeological risks in underground projects.

6.2 Future research

Methods, tools and estimates presented in this thesis offer possibilities for further development and application:

- Hydrogeological risks in underground construction results from the hydrogeological conditions, thus the hydrogeological setting, where the tunnel is located, the design of the facility and the objects at risk in the near area. The framework and methods presented in this thesis have been applied on projects in different project phases (planning and construction). In all case studies presented here, the localization of the tunnel has already been decided upon and the risks associated with these conditions are thus managed with the risk management process. However, there is no limitation for using the framework to evaluate alternative localizations for the tunnel with respect to hydrogeological risks. The alternatives to be evaluated could then constitute different locations, the costs, the different level of measures needed for the different locations, and the benefits of the reduced risks of negative impact on groundwater dependent objects. Thus, the hydrogeological risk management process has the potential to be used very early in a project to evaluate where the tunnel can be built with as little effects on the groundwater as possible and whereas the cost for measures to reduce groundwater risks is low. This could potentially result in a lower construction cost for the tunnel and lower hydrogeological risks.

- The usage of CEA and CBA and their specific consequential ethical point of departure enables a coherent comparison of benefits and costs, but in a broader context such comparisons can be highly controversial. Some risks associated with negative impacts on the environment or on cultural values may be seen as unreasonable to trade against the cost of implementing measures. Two such examples are the intrinsic values of nature or relational values (Stålhammar et al., 2019). Identifying and explaining the presence of such non-economic values would increase the understanding of the limitations of using these methods for risk evaluation.

- The value of information analysis (VOIA) is included in the presented framework in Paper I but has not been conducted within this PhD project. Since the models for risk analysis and risk evaluation must be built on limited amount of data and since collecting data often are time consuming and expensive, the risk evaluation and thus the whole risk management process could benefit if the CBA was complemented with a VOIA. This would provide potential for projects to reduce costs since erroneous decisions in underground construction projects can result in expensive consequences.

- Damage models describing the relationship between groundwater impact and negative impact on groundwater dependent objects must also be developed to be able to include as many objects at risk and thus consequence items as possible in the analysis. There are many methods available for assessing building damages as a consequence of subsidence (see e.g., Wikby et al. (2024) for a thorough review of methods). However, models describing the relationship between leakage- groundwater drawdown and negative impacts on groundwater dependent ecosystems such as wetlands and rivers are not as thoroughly investigated, although there are examples (see e.g., Vincenzi et al. (2022).

- As a final research topic to be mentioned here, primary valuation studies must be conducted to enable monetization of consequences. As indicated by Lundin Frisk et al. (2024), there is a substantial need for new primary calculation studies for geosystem services and ecosystem services whose provision is affected by groundwater level decline since existing studies are limited which limits benefit transfer. The risk valuation approach adopted in this work is primarily based on an expected damage framework, where the benefits of risk-mitigation measures are quantified as reductions in expected consequences. This approach does not fully capture individuals' preferences with respect to changes in risk per se, including attitudes toward uncertainty and risk aversion. Future research could therefore focus on *ex ante* valuations, i.e., the valuation of risk changes before it is known which outcome will occur.

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