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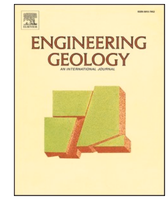

Identification of benefits and costs from the reduction of hydrogeological risks in underground construction

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ABSTRACT

Implementing measures to reduce hydrogeological risks from underground construction below the groundwater table is often expensive. Cost-benefit analysis (CBA) assesses whether measures give a positive societal net benefit and thereby indicates how society's limited resources can be used efficiently. For a CBA to be valid, all costs and benefits for all affected stakeholders should be included. This implies that a thorough and comprehensive identification of cost and benefit items is the crucial basis for the development of a CBA. In this paper, a novel and comprehensive approach for identifying benefit and cost items of implementing hydrogeological risk-mitigation measures is presented for application in underground construction. The novelty lies in the procedure of integrating hydrogeological knowledge of common underground type settings with the cascade model—a well-established framework for linking natural, social, and economic systems (Haines-Young and Potschin-Young, 2018)—and categorizing leakage-induced risks, and thereby the potential benefits of mitigating these risks have been systematically identified. Relevant groundwater leakage-induced cascades are presented in a general format, together with examples from the literature for providing a user-friendly tool for risk identification that considers the whole chain of events from groundwater impact to social and economic consequences. The combination of using the basis of the cascade model together with international literature 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. An identification of cost and benefit items in two railway tunnel projects in Sweden is also presented as a qualitative CBA to demonstrate the usability of the risk cascades as a basis for identification of items to subsequently be monetized in a quantitative CBA. Finally, the paper discusses the upcoming steps, challenges, and strategies to handle them, associated with obtaining a complete quantitative CBA.

1. Introduction

1.1. Background

Increasing global urbanization leads to a land-use conflict which results in higher demand for locating infrastructure such as roads and rails below the ground surface (Huggenberger et al., 2011). 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 and Jones, 2020; Ayalon et al., 2016; Cowie et al., 2012; Forman and Alexander, 1998; Rico et al., 2007; Volchko et al., 2020). However, construction below the ground surface and the groundwater table is often associated with groundwater leakage and environmental impacts due to a decline in groundwater levels in surrounding aquifers. 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).

Risks associated with leakage-induced groundwater drawdown are of economic, social, and environmental character. The objects at risk consist of all groundwater-dependent objects and processes such as subsidence sensitive buildings and facilities (Boone, 1996), groundwater

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extraction (Chae et al., 2008), groundwater ecosystems (GEs) (Longley, 1981), archeological remnants (Holden et al., 2009), groundwater-dependent ecosystems (GDEs) such as wetlands and lakes (Kværner and Snilsberg, 2008), and forest growth (Behzad et al., 2022), to mention a few. Identifying these risks is often a necessity within the framework of the environmental impact assessment (EIA). To maintain the benefits that the undisturbed groundwater system provides, the risks associated with leakage-induced groundwater drawdown must be managed. There are several possible measures for reducing these risks, such as sealing measures (Luciani and Peila, 2019; Panthi and Nilsen, 2005), artificial recharge (Cashman and Preene, 2001; Zeng et al., 2019; Zheng et al., 2019), or measures directed directly towards the objects at harm, for example reinforcement measures to subsidence sensitive buildings (Díaz et al., 2018; Ding et al., 2015).

A major part of the *risk management* process is *risk assessment* (ISO, 2018), and one approach to assess leakage-induced risks is to conduct a risk-based cost-benefit analysis (CBA) (Merisalu et al., 2021; Merisalu et al., 2023). CBA is a widely used method for assessing the societal profitability of a project (e.g., implementing a measure) by comparing positive (i.e., benefits) and negative (i.e., costs) consequences for human wellbeing in both present and future generations (Boardman et al., 2018; Johansson and Kriström, 2016). Recent studies where CBA has been used for risk evaluation in the context of environmental management include e.g., Drenning et al. (2023), Machairas and Varouchakis (2023) and Gu et al. (2024). In principle, a CBA compares the costs and benefits by calculating a net present value (NPV) of implementing a measure relative to a reference alternative. In the context of risk-mitigation measures to reduce the leakage-induced groundwater drawdown risks, the benefits comprise reduced risks and other positive consequences, and the direct and future costs associated with implementing the measures constitute the costs. 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). This implies that a thorough and comprehensive identification of cost and benefit items is crucial for the CBA to be a robust decision support tool that can be accepted by both the owner of the underground project and the affected stakeholders.

Various risks associated with leakage to underground constructions and the cost of implementing risk-mitigation measures have, to a wide extent, been identified and presented in the literature. However, this information is widely distributed, and carrying out a literature search to identify risks, and cost and benefit items for each new underground project is likely to be impracticable, time-consuming, and not financially viable. Existing literature also most often focuses on only one part of the chain of events of leakage induced consequences, thus not considering both the natural and the social and economic system. This can lead to missing, leaving out, and/or ignoring relevant risks of groundwater impact from underground construction and thus relevant costs and benefits associated with implementing measures resulting in unsubstantiated decisions. There is therefore a need for the novel contribution of this paper, i.e., a cross-system, robust and easily understandable method for identifying cost and benefit items to enable a comprehensive CBA in the specific context of risk-mitigation measures to reduce the leakage-induced groundwater drawdown risks. By integrating hydrogeological knowledge of common underground type settings with the cascade model—a well-established framework for linking natural, social, and economic systems (Haines-Young and Potschin-Young, 2018)—and categorizing leakage-induced risks, the potential benefits of mitigating these risks have been systematically identified.

1.2. Aim and objectives

The aim of this paper is to present a method for identifying relevant cost and benefit items of implementing hydrogeological risk-mitigation measures in underground construction that enables CBA of such measures.

Specific objectives are to:

(i) Use the principles of the cascade model (Haines-Young and Potschin-Young, 2018) to identify the environmental impact of hydrogeological risks due to groundwater leakage, by considering the changes to the properties and functions of the hydrogeological system, as well as the services and benefits to human wellbeing provided by the system.
(ii) Present relevant and common cascades associated with groundwater leakage to demonstrate the complexity and variety of the many risks that could be triggered, as well as the potential benefits of implementing risk-mitigation measures.
(iii) Present relevant cost items of implementing risk-mitigation measures to reduce groundwater leakage induced risks.
(iv) Demonstrate the usability of the identification methods through two case studies constituting two different hydrogeological settings (urban and rural) with different types of objects at risk, where the cost and benefit items that need to be subjected to economic valuation for evaluation in a CBA are identified and described.
(v) Present strategies and discuss challenges associated with obtaining a complete CBA through quantification of effects and monetization of benefits and costs.

2. Theory

2.1. The risk management process and its relationship to cost-benefit analysis

The risk-based cost-benefit analysis framework described in Merisalu et al. (2021) forms the basis for this paper. The framework is based on the risk management process according to ISO (ISO, 2018) and includes the necessary steps to perform a CBA to evaluate risk-mitigation measures based on their social profitability, expressed by the net present value (NPV). In Fig. 1, a simplified and condensed version of the framework highlights how a CBA can be integrated into the following four parts of the risk management process: 1) establish the context, 2) risk identification, 3) risk analysis, and 4) risk evaluation. Note that the risk management process as well as the CBA process are iterative, i.e., all models are run and updated several times before the evaluation of risk-mitigation measures is finalized. The following paragraph describes the four steps in a simplified two-iteration run.

Establishing the context includes defining the aim and purpose of risk management. The risk-based CBA is about evaluating risk-mitigation measures based on economic valuation of costs and benefits where the measure with the highest NPV is recommended to be implemented, given restrictions for measure selection implied by, e.g., laws and social norms (Merisalu et al., 2021). The aim and purpose may be updated for the different iterations but most often stay constant. In the risk identification step, all possible risks are identified in the first iteration by using the principles of the cascade model. In the second iteration, additional risks may be added. In this run, risks remaining after implementing risk-mitigation measures are identified, thus indicating potential benefits of risk reduction (see Section 2.2). The risk analysis includes quantification of probabilities and economic consequences of identified risks (expected negative consequences). Risks and benefit items that cannot be quantified because of, e.g., lack of data, should be described in qualitative terms. In a second iteration, the probabilities and economic consequences of risks after implementation of risk-mitigation measures are quantified. The reduction of risks due to measure implementation constitutes benefits. The risk evaluation step aims to identify which risks that need treatment and which risks that need to be prioritized for treatment implementation. In a second iteration, this step includes quantification of the costs (probabilities and economic consequences) for implementing measures (see Section 2.2).

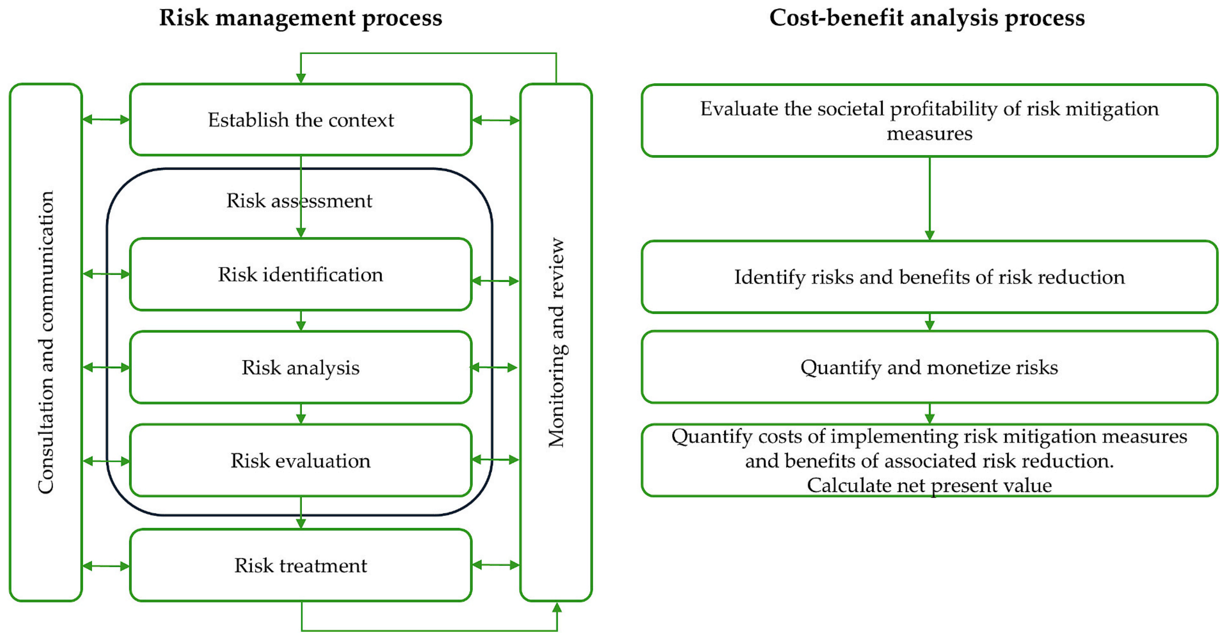

Fig. 1. The process of a risk-based cost-benefit analysis within the framework of the risk management process. The horizontal placement of the CBA steps indicates the corresponding stage within the risk management process to which each step belongs.

Cost items that cannot be quantified are described in qualitative terms. Once both benefits and costs are quantified, the NPV of the measures judged to be adequate for treatment are calculated.

2.2. Risk expectancy, benefits, costs, and net present value

A risk-based CBA can be based on an expected damage setting through defining the total risk expectancy, R_{tot}, associated with a risk-mitigation measure, *i*, as (Bedford and Cooke, 2001):

$$R_{tot\ i} = E[K_{F\ i}] = \int_0^1 K_{F\ i}(P_{F\ i})dP, \tag{1}$$

where P_F is the probability of an undesired event occurring (failure, *F*), and K_F is the economic consequence of that event, i.e., its costs to society. The total risk, R_{tot}, is the expected value of the consequence, $E[K_F]$, considering scenarios for all included events and their associated probabilities. Note that the risk calculations provide information on the total risk and that the consequences of each contributing scenario can be displayed. For example, the contribution of project internal risks can be compared to the contribution of external risks.

In a CBA of implementing a risk-mitigation measure, the associated decrease in risk expectancy in comparison to a reference alternative, *ref*, constitutes the benefits of that measure. The reference alternative is often defined as the null alternative of not implementing any measure. The benefits, *B*, of implementing a measure *i* are thus:

$$B_i = R_{tot\ ref} - R_{tot\ ref}. \tag{2}$$

The expected damage setting of Eqs. (1)-(2) is commonly used in practice in CBA, because data on the damage costs in K_F are often easily available (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. We stick to the expected damage setting here and discuss its pros and cons further in Section 5.

The total expected cost, M_{tot}, associated with implementing 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 consequence of that event, measured here as the costs to society of implementing the measure. The total measure cost, M_{tot}, is the expected value of the consequence, $E[L_M]$, considering scenarios for all included events and their associated probabilities. Given a reference alternative of not implementing any risk-mitigation measure, it follows that $M_{tot\ ref}=0$.

In a CBA of implementing 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 a measure, *i*, are thus:

$$C_i = M_{tot\ i} - M_{tot\ ref}. \tag{4}$$

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

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

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 the measure *i*, $C_{i,t}$ is the costs during year *t* of implementing the measure *i*, and *r* is the social discount rate.

2.3. The cascade model

Frameworks for assessing ecosystem services suggest a structure for analyzing how the hydrogeological system supports human wellbeing through various services. Such frameworks include The Economics of Ecosystems and Biodiversity (TEEB) (TEEB, 2010), and the more recent Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin-Young, 2018). Other frameworks that supplement CICES include geosystem services (Fox et al., 2020; Frisk et al., 2022; Van Ree and Van Beukering, 2016), and water system services (Gärtner et al., 2022). In order to identify the societal risks associated with groundwater leakage, and evaluate the benefits of reducing these risks, a model is needed that describes how changes in the natural (pre)conditions can result in consequences for society. The cascade model (Haines-Young and Potschin-Young, 2018), which is a cornerstone in the CICES framework and often used to demonstrate how changes in nature can result in changed provision of ecosystem services and subsequently consequences for human wellbeing, allows us to do this.

In this paper, the principles and structure of the cascade model, as applied for identification of water system services in Gärtner et al. (2022), are used to identify hydrogeological risks associated with groundwater leakage and thus the potential benefits of implementing risk-mitigation measures. Groundwater as such is an abiotic feature, but it has the potential to sustain ecosystems within aquifers, in wetlands, and in recipients. Our usage of the cascade model therefore includes both biotic and abiotic properties and functions of the hydrogeological system as recommended by Van der Meulen et al. (2016). The cascade model applied to identifying benefits of a risk-mitigation measure is divided into two main parts: 1) the hydrogeological system (both the abiotic and biotic parts), and 2) the social and economic systems (Fig. 2). 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). Finally, various types of values might be associated with this benefit. The relevant type of value in a CBA context is economic. When groundwater leakage to an underground construction occurs, the properties and functions of the hydrogeological system may change (Δ), thus putting the provided services and associated benefits at risk (see Eq. (1)). A risk-mitigation measure may limit these changes and thus reduce the risk of negative impacts on human wellbeing. The benefits gained from the risk-mitigation measure thus constitute the changed risk expectancy (Δ Risk) gained from implementing the measure (see Eq. (2)).

The cascade model framework allows for a detailed mapping of consequences by not just describing the system as one event – one consequence. Instead, the model incorporates the understanding that one event can result in several other events and that one consequence can result in several other consequences. As an example, the complex chain of events that need to occur for a groundwater leakage to cause consequences, e.g., subsidence damage to buildings, depends on the dynamic interactions between the components of the cause-effect chain that forms the cascade model (Merisalu et al., 2021; Sundell et al., 2019). These components constitute the events, e.g., groundwater leakage into the underground facility, that may trigger changes to properties and functions such as groundwater pressure head reduction, reduction in pore pressure, and subsidence. The risks stemming from these changes also constitute a component in the cascade model, as do the resulting consequences in terms of economic value if these risks are not managed. Whether each step of the model is initiated depends on several factors such as the magnitude of the groundwater leakage, hydraulic connection between aquifers, boundary conditions of the hydrogeological system, duration of groundwater drawdown, properties of the clay, and type of foundation of the buildings (Merisalu, 2021; Sundell, 2018). The risk of damage to a building can be considered both a primary and secondary risk. Damage to a building is a primary risk that can result in the secondary risk of need to conduct repair work. These risks can in turn result in economic consequence items that constitute both direct and indirect costs. In this case, the direct costs can include the cost of reparation (Merisalu et al., 2023; Providakis et al., 2020; Van den Born et al., 2016), while the indirect costs can include, e.g., lost revenues for businesses located in the damaged building (Abidin et al., 2015; Kok and Costa, 2021), and a decline in property and real-estate values in the area (Willemsen et al., 2020; Yoo and Perrings, 2017). It is therefore important to be aware that a groundwater leakage does not necessarily result directly in economic consequences but should instead be seen as an event that may trigger a chain of events that could result in such consequences.

3. Method

3.1. Identification of risk cascades and costs of measure implementation

The aim of the identification process was to identify relevant

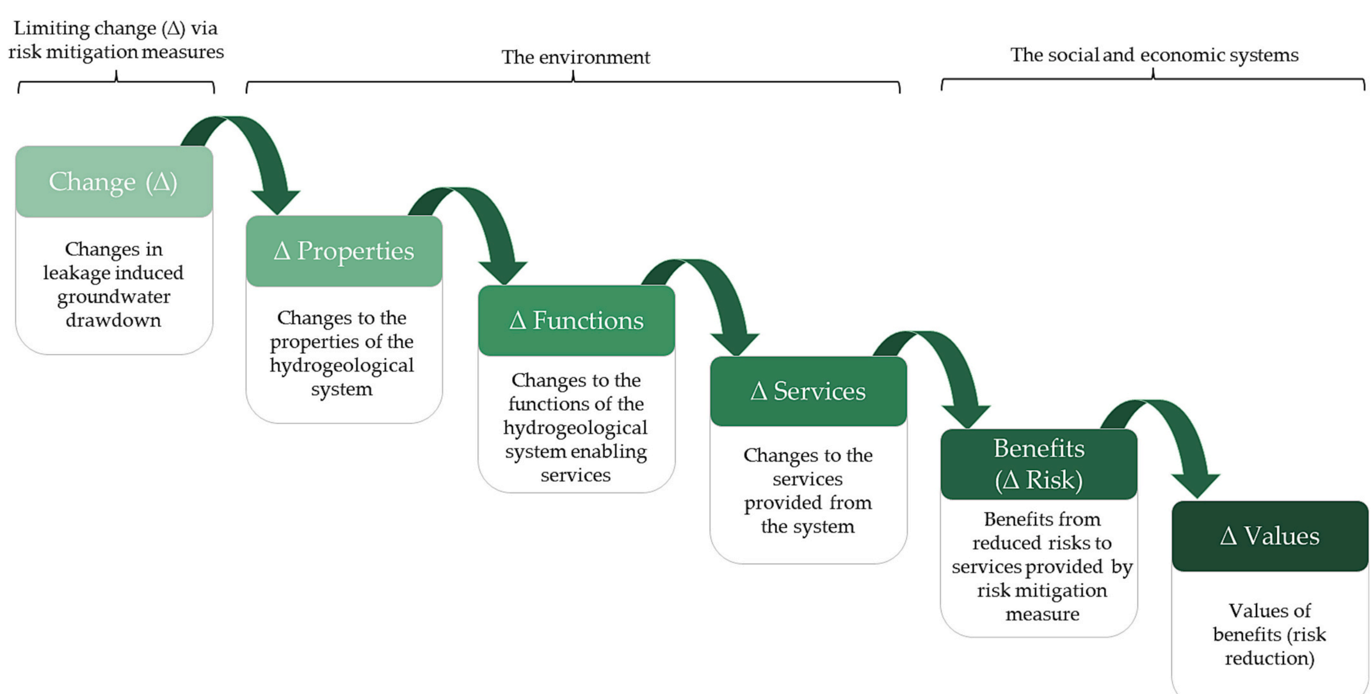

Fig. 2. Conceptualization of linkages between limiting/reducing changes (Δ) in properties, functions, and services of the hydrogeological system and the reduced groundwater leakage induced risks, i.e., a benefit (Δ Risk) which has an economic value. Modified from Haines-Young and Potschin-Young (2018).

cascades and potential environmental risks that could be triggered by groundwater leakage-induced changes to the properties of the hydrogeological system, as well as relevant risk-mitigation measures and the costs associated with implementing them. This was carried out by searching relevant literature and conducting workshops with experts within the field of underground construction and EIAs. The workshops and the literature searches were conducted parallel to each other, with input from the workshops iteratively generating input to the literature search and vice versa.

3.1.1. General method of the identification process

The first step of the risk identification process was to identify relevant hydrogeological properties that could change as an effect of groundwater leakage. When a groundwater leakage into an underground construction occurs, it is the surrounding water-bearing units (often aquifers and aquitards but also surface-water bodies) that are the sources of the inflowing water (Gustafson, 2012). The groundwater leakage is not likely to result in major changes to the properties of the aquifer material, e.g., porosity, grain size distribution, hydraulic conductivity, or compressibility. Instead, it is the properties of the groundwater within the aquifer that are at risk of considerable changes. In this study, the properties identified that may initiate risk cascades are abiotic and include: (1) reduced pressure heads in confined aquifers, (2) lowered groundwater table and reduced saturated thickness in unconfined aquifers, and (3) the changed gradient resulting from changes to properties (1) and (2). The next step was to identify relevant functions, services, and the risks that could be triggered by these changed properties. Even if the identified properties are abiotic, the functions can be both biotic (e.g., the functions that are maintained by organisms in the groundwater ecosystem), and abiotic (e.g., the regulation of stress in confining compressible soils). The events in one cascade can also trigger feedback loops and thus initiate new cascades. As an example, groundwater leakage can decrease the groundwater table in surrounding aquifers and thus initiate a primary cascade of decreased saturated thickness (storage) of an aquifer. This can subsequently give rise to decreased baseflow in a recipient which forms a secondary cascade. The third step of the identification process was therefore to identify the potential feedback loops initiating secondary cascades.

For the identification process of risks other than the ones associated with environmental impact, focus was on the consequences of groundwater leakage for both the construction and operation of the underground facility.

The identification process of cost items began by identifying common risk-mitigation measures for managing hydrogeological risks, followed by identifying cost items associated with implementing these measures. There are a wide variety of techniques available for reducing groundwater leakage into an underground construction, e.g., pre- and post-grouting with agents of different chemical composition (Butrón et al., 2010; Garshol, 2003; Grøv, 2002; Grøv and Woldmo, 2012; Langford et al., 2022; Panthi and Nilsen, 2005), water proofing membranes and linings (Dammyr et al., 2014; Luciani and Peila, 2019; Maidl et al., 2008), and freezing methods (Pimentel et al., 2012). However, since the purpose of the identification process was limited to identifying cost items that are relevant for a comparison of costs and benefits of implementing measures, the gross lists of cost items were expressed in generic rather than technique-specific terms. This is likely to make the list usable for upcoming techniques as well.

3.1.2. Workshops

Three workshops were carried out within the framework of identifying risk cascades and costs of measure implementation. Structured brainstorming was chosen because it is an efficient way of rapidly generating a large number of ideas by encouraging people to be creative and focus on generating as many ideas as possible (Oguz Erkal et al., 2021). The workshops had clearly defined objectives and all participants were given the opportunity to present their ideas one by one. Table 1 in Supplementary material 1 presents the focus areas for the workshops as well as the number of participants and their expertise. In all workshops, participants were asked to answer the questions individually, followed by a presentation of their results to the other participants, and finally group discussions. For workshops 1 and 3, the group discussions were carried out in two subgroups due to the larger number of participants.

3.1.3. Literature search

A narrative literature review (Pautasso, 2019) was conducted to collect peer-reviewed articles, conference papers and grey literature about cascade items, common risk-mitigation strategies and their associated consequences. Only texts written in English were included in the search.

For the identification of risks, the first part of the literature search covered the hydrogeological aspects of the environment by focusing on identifying the properties and functions of the hydrogeological system that could be changed due to a groundwater leakage, and the services dependent on these properties and functions. The second part of the literature search focused on the consequences for the social and economic systems, i.e., how services from the environment are used by society and thus the risks associated with changes in the environment. Note that an underground construction, e.g., a tunnel, acts as a drain in the hydrogeological system, just like an extraction well, and can cause a groundwater drawdown in the surrounding aquifers (Gustafson, 2012). The search was therefore not limited to the effects of underground construction itself as a trigger of groundwater drawdown, but also included other relevant cascades and events that can induce drawdown, such as a result of over-pumping.

For the identification of costs, the literature review focused on identifying common risk-mitigation measures as well as the costs associated with implementing these measures.

3.2. Case study application

Two case studies were used to demonstrate the usability of the methods for identifying risks, and benefits and costs of risk-mitigation measures. These were the Westlink and the Eastlink, both involving rail tunneling construction projects, but with two different hydrogeological settings (Fig. 3) and different types of objects at risk.

3.2.1. Case study 1, The Westlink and Haga station area

This case study comprises the Haga station area as a part of the Westlink rail tunnel in central Gothenburg (SW Sweden). The Westlink is built to increase the local and regional rail capacity and consists of 8 km of rail, 6 km of which is built underground, and three new underground stations (STA, 2014). The Haga station part of the tunnel is constructed in both rock and soil, which results in an open deep excavation in the city center.

The area is characterized by cultural historical buildings and urban green spaces. In the Haga area, buildings are small with wooden facades. In the neighboring Vasastaden area, larger stone buildings dominate. The Haga church, the library, and the university building are landmarks in the area. Today, the buildings are used for residential as well as commercial purposes. The structures at street level house smaller shops, cafes, and restaurants. There are tracks for trams and lanes for cars, buses, bicycles, and pedestrians within the area. The subsidence in the area as well as the sensitivity of the buildings have been analyzed and confirmed (see e.g. Wikby et al. (2024)).

The geological stratigraphy in the area (from the bottom up) is composed of fractured granitic gneiss covered with a thin layer of glacial till. The fractured rock and the till constitute two partly confined aquifers that are unconfined in conjunction with the bedrock outcrops. The till is mainly covered by glaciomarine clay prone to subsidence with varying thickness, shallow in conjunction with the bedrock outcrops and deeper towards the Göta river valley. On top of the clay, there are layers of abrasion sediments (sand) and filling material with varying thickness

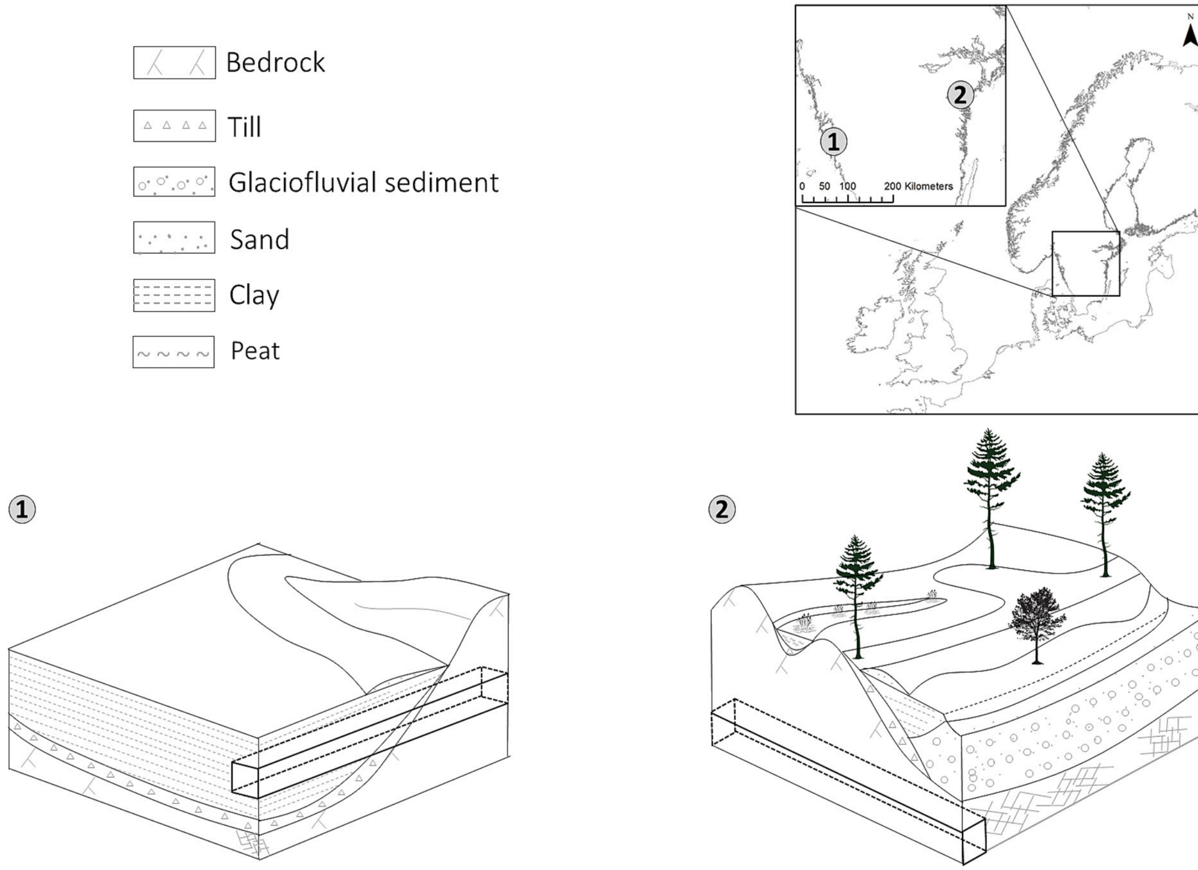

Fig. 3. Illustration of the hydrogeological settings of the two case studies indicating the location of the tunnel crossing the valleys. To the left, case study 1 – the Westlink as a tunnel located in both rock and soil, and to the right, case study 2 – the Eastlink as a tunnel located in bedrock below the soil-filled valley.

up to a few meters. The sand and filling material comprise an unconfined aquifer with hydraulic connection to the lower till aquifer at the valley slopes in conjunction with the bedrock outcrops. In summary, three aquifers are thus present in the area: 1) the fractured bedrock, 2) the confined till, and 3) the sand and filling material. The hydraulic connection between the aquifers implies that a groundwater leakage into the bedrock tunnel or the excavation shaft can cause a groundwater drawdown in all aquifers.

The risk-mitigation strategy for the tunnel includes sealing the tunnel to decrease the groundwater leakage. The sealing mainly consists of pre-grouting with preparation for post-grouting if the pre-grouting is not sufficient to reduce the inflow of groundwater to a level that corresponds to the legal requirements. The risk-mitigation strategy also includes artificial recharge of groundwater through recharge wells into both the lower confined and the upper unconfined aquifers with the purpose of maintaining stable groundwater levels and counteracting leakage-induced groundwater drawdown.

3.2.2. Case study 2, The Eastlink and Getå catchment

This case study consists of a part of a rail tunnel project in a new railway between the cities of Järna and Linköping (SE Sweden), aiming at increasing accessibility, reducing travel time, and increasing the punctuality of the trains in the region (STA, 2023b). The whole Eastlink project covers 160 km of rail including seven rock tunnels. The case study is in the Getå stream catchment, a 9.9 km^2 area with an outlet into the Baltic Sea.

The area is characterized by a typical Swedish geological setting with a bedrock landscape partly covered with till and peat, and clay-filled valleys. Small lakes are scattered across the area. The valley has low population density and is mostly covered with forest, agricultural land, and pastures. The Getå stream runs through the valley and has eroded the upper soil layers, resulting in a ravine. Springs are present in several places at the edges of the stream, which indicates a mainly gaining stream for most part of the hydrologic year that is partly fed by groundwater.

The geological stratigraphy in the valley (from the bottom up) consists of fractured granitic gneiss with one major brittle deformation zone that coincides with the deeper parts of the valley. This deformation zone is characterized by highly fractured rock with high hydraulic conductivity. The fractured rock constitutes a partly confined aquifer. A layer of glacial till with varying thickness is present on top of the rock. The deepest part of the valley also has a glaciofluvial deposit that is mainly covered with glaciomarine clay and/or silt but outcrops in the northern part of the valley. The till and the glaciofluvial deposit mainly comprise confined aquifers with smaller unconfined parts. The till/glaciofluvial aquifer is recharged where the deposits are unconfined and from the surrounding rock aquifers. The clay is prone to subsidence and has varying thickness. On top of the clay, there are layers of abrasion sediments (sand) with varying thickness up to a few meters. The thickness of the soil deposits in the valley is up to 30 meters in the deepest part. The abrasion sediments comprise unconfined aquifers with hydraulic connection to lower aquifers at the valley sides in conjunction with the bedrock outcrops and at the unconfined part of the glaciofluvial deposit. In summary, three aquifers are present in the area: 1) the partly confined fractured bedrock, 2) the partly confined till and glaciofluvial material, and 3) the unconfined sandy abrasion sediments. The hydraulic connection between the aquifers implies that a groundwater leakage into the tunnel can cause a groundwater drawdown in all three aquifers.

The risk-mitigation strategy for the tunnel consists of sealing the tunnel to decrease the groundwater leakage, mainly through pre-grouting with preparation for post-grouting if pre-grouting is not sufficient to reduce the inflow of groundwater to a satisfactory level. Another part of the strategy is to lead the groundwater that leaks into the tunnel back to the Getå stream with the purpose of maintaining a sufficient baseflow. According to Swedish regulation, the stream must not be impacted beyond environmental quality standards. This means that the flow in the creek cannot be reduced by more than approximately 5% (STA, 2022).

4. Results

4.1. Identified risk cascades for environmental impact

Three hydrogeological risk cascades were identified by the literature search and workshops conducted. Each of the cascades is initiated by a change in one of the following properties: (1) decreased pressure head, (2) decreased saturated thickness (storage), and (3) changed gradient.

The change in these properties can give rise to a unidirectional cascade, as well as initiating feedback loops that can form new cascades. The cascades should not be considered as final or exhaustive but as: 1) a demonstration of how the cascade model can be used to identify leakage-induced risks, and 2) an exemplification of the variety of risks that changes in these properties can entail. The text below about each of the three cascades provides generic examples of chains of consequences that are relevant to consider. Note that there are risks included in the figures that may constitute positive consequences and not just negative ones.

4.1.1. Decreased pressure head

Decrease in pressure head (Fig. 4) in a confined aquifer can give rise to pore pressure reduction in overlying soft soils and thus an increase in effective stress with instability of the ground and subsidence (Chai et al., 2004; Huang et al., 2012; López-Fernández et al., 2012; Sundell et al., 2019; Yoo, 2016; Yoo et al., 2012).

Subsidence creates a risk of damage to buildings and infrastructure (Boone, 1996; Clarke and Laefer, 2014; Kok and Hommes-Slag, 2020; Providakis et al., 2020; Sundell et al., 2019; Zheng and Diao, 2016). Reparable damage may give rise to costs for investment in new materials, emissions from manufacturing the material, and emissions from the machinery used for the reparation work. If traffic routes need to be closed this can result in increased travel time, increased emissions from traffic, and decreased traffic safety. Other costs associated with reparation work are due to transport of material and equipment, which in turn can impact traffic, cause lost revenues for businesses located in damaged buildings, and create increased noise and inconvenience for residents (Delgado-Galván et al., 2010; Gilchrist and Allouche, 2005; Grigg, 2013; Kok and Costa, 2021). In addition to the consequences associated with reparations, damage to historical buildings may result in historical and cultural heritage losses (Klamer, 2014), damaged infrastructure such as sewer pipes can contaminate the groundwater (Pal et al., 2014; Pedley and Howard, 1997), while damage to water pipes can result in water shortages that may affect private consumers, the public sector, and private businesses (Luis et al., 2019). An area suffering from subsidence may also be subject to market resistance and therefore face property value losses (Willemsen et al., 2020; Yoo and Perrings, 2017).

Another consequence of ground movement and subsidence is changes to the natural water systems which in turn may decrease the drainage of an area and thus increase the risk of flooding (Abidin et al., 2015). Subsidence can also directly result in an expansion of flood risk areas (Abidin et al., 2015; Venvik et al., 2020). Direct impacts of flooding constitute the direct physical contact between floodwater and humans, and assets, such as buildings and infrastructure. Indirect impacts occur outside of the flood event, such as disruptions of supply chains, lost productivity, and lost revenues for businesses (Abidin et al., 2015; Bubeck et al., 2017; Fowler, 1981).

4.1.2. Decreased saturated thickness

The second cascade is initiated by changes to the property of saturated thickness and thus storage of the aquifer(s) surrounding the underground construction (Fig. 5). Reduction in storage will decrease the amount of water available for GEs located within the aquifer (Stumpp and Hose, 2013), as well as GDEs that needs a certain depth to the groundwater level to function (Griebler et al., 2019). A reduction in saturated thickness can also give rise to a decreased baseflow in recipients (Attanayake and Waterman, 2006; Vincenzi et al., 2009), which will also decrease the amount of water available for GDEs. These changes may in turn decrease access to services provided by GEs and GDEs. The following paragraphs will present examples of services and benefits provided by GEs and GDEs. For a full mapping of benefits and potential risks of decreased saturated thickness, see, e.g., Haines-Young and Potschin-Young (2018), Gärtner et al. (2022), Kløve et al. (2011a) and Griebler and Avramov (2015).

One important service provided by both GEs and GDEs is the potential to extract or use water for energy. A reduction in saturated thickness can reduce the possibility of utilizing the aquifer for energy by using, e.g., groundwater-based heat pumps (Lund et al., 2005), while a decrease in baseflow in recipients can reduce the possibility of harnessing hydropower in surface-water bodies (Gärtner et al., 2022; Kløve et al., 2011b). A reduction in capacity may force the owner to seek less sustainable alternatives to compensate for the capacity loss. As an example, groundwater-based heat pumps can save greenhouse gases compared to alternative technologies (Bayer et al., 2012). Another important service provided by GEs and GDEs is the extraction of water for human or animal consumption, irrigation, or use as a material or other type of input to consumption or production (Chae et al., 2008; Gisbert et al., 2009; Golian et al., 2020; Gärtner et al., 2022). A reduced capacity to extract water can cause water shortages that may affect private consumers, the public sector, and private businesses (Luis et al., 2019). There may also be a need for a new water extraction facility, resulting in investment costs for construction and possibly also land claims. Construction involves emissions from machinery and materials and associated transports, the latter of which may also cause increased travel and transportation time and decreased traffic safety.

Subsurface ecosystems and more specific GEs constitute habitats for diverse microbial communities and metazoan fauna (Boulton et al., 2008; Deharveng et al., 2009; Griebler and Avramov, 2015; Griebler and Lueders, 2009; Humphreys, 2006; Korbel et al., 2017; Longley, 1981). The diversity and activity of these organisms provide a multitude of services and benefits for human wellbeing because of both use and non-

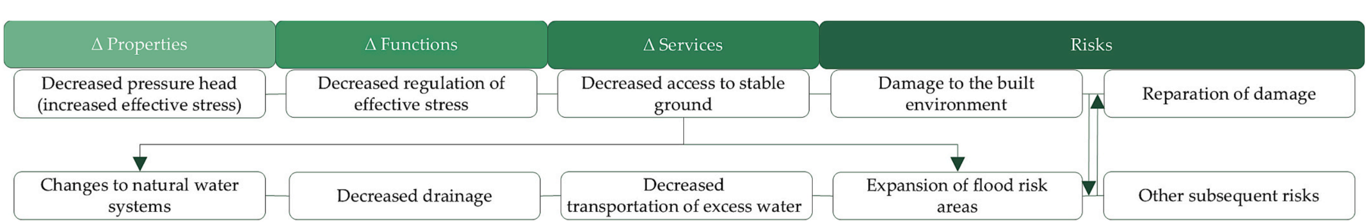

Fig. 4. Identified subsidence risks triggered by decreased pressure head and decreased access to a stable platform to build upon/within. The cascade should be read from left to right and top to bottom. Arrows are present to highlight exceptions regarding direction or simply to guide the reader.

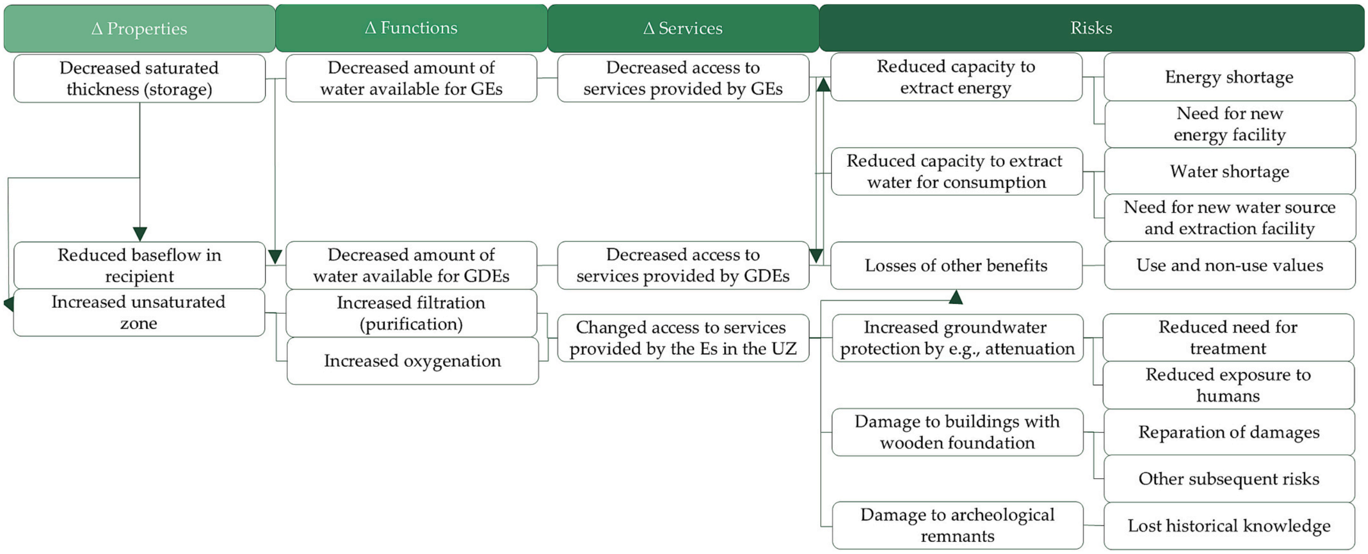

Fig. 5. Identified risks of changes triggered by decreased saturated thickness and thus reduction in storage of an aquifer. The cascade should be read from left to right and top to bottom. Arrows are present to highlight exceptions regarding direction or simply to guide the reader. GEs, GDEs, Es, and UZ refer to groundwater ecosystems, groundwater-dependent ecosystems, ecosystems, and unsaturated zone.

use values. The microbial community in GEs plays an important role in maintaining good water quality, since it can biodegrade contaminants and pathogens (Aamand et al., 1989; Griebler and Avramov, 2015; Gärtner et al., 2022). GEs can also be a sink or a source of nutrients and carbon (Griebler and Avramov, 2015; Gärtner et al., 2022). Groundwater can convert, retard, or immobilize N and P (Lewandowski and Nützmann, 2010; Rivett et al., 2008), but a groundwater drawdown or contamination may decrease the attenuation of nutrients (Griebler et al., 2019) and thus increase the likelihood of eutrophication in recipients. Aquifers are constantly fed with organic carbon which gets mineralized by respiration and biomass production. A decreased microbial CO_2-fixation may therefore add to global climate change as well as reduce groundwater quality (Griebler and Lueders, 2009). A habitat reduction for organisms inhabiting GEs may also decrease intellectual and representative interactions with the natural environment, which could limit the conduct of scientific investigations and outdoor education (Gärtner et al., 2022).

GDEs include all ecosystems that are reliant on a supply of groundwater to maintain their ecological structure and function (Kløve et al., 2011a; Murray et al., 2006). GDEs, e.g., springs, lakes, rivers, and wetlands (Bertrand et al., 2012) can contribute to the regional natural (biotic and abiotic) diversity since they provide habitats for a wide variety of flora and fauna (Mitsch et al., 2015; Okruszko et al., 2011) and are often considered sites of great beauty (Gärtner et al., 2022). Altered flow regimes may alter and negatively impact the habitat for many of these species (Bunn and Arthington, 2002; Orellana et al., 2012), resulting in changed opportunities to harvest, e.g., food, material, fuel such as peat, and genetic material (Gärtner et al., 2022; Mitsch et al., 2015). The growth of trees may be reduced due to artificial groundwater lowering (Behzad et al., 2022; Liu et al., 2019). GDEs, such as peatbogs and swamps, can also work as a sink for CO_2 and a lowered groundwater table can thus increase CO_2-emissions (Huang et al., 2021; Moore and Knowles, 1989). Furthermore, GDEs contribute to maintaining good water quality by biodegrading contaminants and pathogens (Kløve et al., 2011a; O'geen et al., 2010) and converting, retarding, or immobilizing N and P (Alan Yeakley et al., 2016). Finally, GDEs often constitute sites that are important for intellectual, representative, physical, and experiential interactions with the natural environment through, e.g., tourism and recreation through fishing, swimming and nature watching (Gärtner et al., 2022).

A decreased saturated thickness also results in an increased unsaturated zone. Many ecosystem services can be linked to the soil biota and their interactions within their physical and chemical environment (Brussaard, 2012; Thomsen et al., 2012; Wall et al., 2004). An increased unsaturated zone can change the access to these ecosystem services. One example of such an ecosystem service is the regulation of microbial contaminants through attenuation (Candela et al., 2007; Ward et al., 2000). Thus, the purification of recharging groundwater can increase. An increased unsaturated zone can also increase the aboveground biomass, such as trees in, e.g., peatlands (Laiho et al., 2003; Murphy et al., 2009); and it can increase oxygenation which can increase the biodegradation of wooden objects, such as the wooden foundation of buildings (Elam and Björdal, 2020) or archeological remnants (de Beer et al., 2012; Holden et al., 2009), which in turn can cause damage to buildings and lost archeological archives and historical knowledge.

4.1.3. *Changed gradients*

The third cascade constitutes changes to gradients induced by changes to groundwater heads (Fig. 6), which in turn can change both the direction and flow velocity of the groundwater (Darcy, 1856). Changed gradients can result in internal erosion (piping) of soils, which is a major risk in deep excavation (Chen et al., 2020; Zhu et al., 2023). Internal erosion can cause failure of retaining walls used in excavations, and damage to surrounding buildings and infrastructure induced by reduced ground stability (Li et al., 2022).

A changed gradient can also alter groundwater chemistry due to an inflow of water with different chemical properties (Chae et al., 2008; Kværner and Snilsberg, 2013; Mas-Pla et al., 2013; Mossmark et al., 2017; Mossmark et al., 2008), which may, subsequently, change the chemistry of the water in a recipient. Changes in the water quality of GEs and GDEs may in turn decrease access to services provided by the GEs and GDEs (Griebler et al., 2019; Katsanou and Karapanagioti, 2017; Kløve et al., 2011a). Changed groundwater chemistry can have an adverse impact on the possibility of extracting clean water for consumption, resulting in health risks, and can also affect the intensity of corrosion or the rate of clogging in underground facilities (Mossmark et al., 2017), as well as in extraction facilities. This can result in a need for increased maintenance and, possibly, increased treatment of the extracted water (Dearmont et al., 1998), which comes with various costs. Further, changes to the gradient can cause mobilization of contaminants (Epting et al., 2008; Huggenberger et al., 2010). Depending

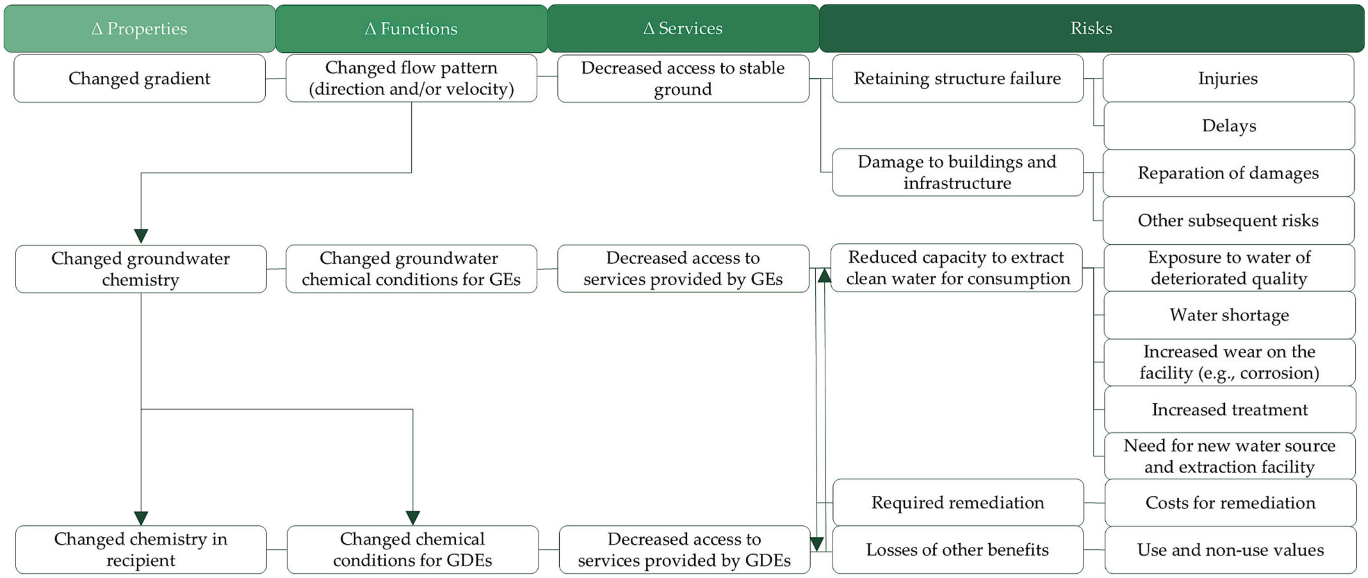

Fig. 6. Identified risks triggered by a changed gradient. The cascade should be read from left to right and top to bottom. Arrows are present to highlight exceptions regarding direction or simply to guide the reader. GEs and GDEs refer to groundwater ecosystems and groundwater-dependent ecosystems.

on national legislation, mobilization of contaminants due to groundwater leakage may require costly remediation. More examples of services provided by GEs and GDEs that face risks are presented in Section 4.1.2.

4.2. Identified risks in the underground facility

Managing groundwater leakage in underground facilities is essential to maintain dry working conditions and operational safety. Groundwater leakage poses risks both during construction and operation, potentially leading to high maintenance and refurbishment costs, as well as costs for disruptions of service (Luciani and Peila, 2019). Large inflows of water into underground constructions can cause fatalities, economic losses, and adverse working conditions (Coli and Pinzani, 2014; Hou et al., 2016). Groundwater leakage can increase maintenance cost during the operation phase by, e.g., inducing the risk of dripping and ice growth, which, according to Butron (2012), can cause shotcrete fallouts, rock fallouts, icicle fallouts, deformation, reduction of the underground facility opening due to ice barriers, icing of the road surface in road tunnels, obstruction of ventilation by ice, damage to vehicles, damage to trains, damage to the lining and damage to the appearance. Groundwater leakage can also induce face and wall instability and degradation of the mechanical properties of the rock, damage to the concrete due to corrosion and freeze/thaw cycles (Luciani and Peila, 2019). The amount of groundwater leakage also affects the drainage system in the underground facility and the facilities/equipment used to get rid of the excess water by, e.g., sedimentation of salts and fine particles clogging the system. A reduction in groundwater leakage can therefore reduce these risks and the associated maintenance costs.

4.3. Identified cost items of implementing measures

This section presents the gross list of cost items and project risks associated with the implementation of risk-mitigation measures. This includes costs that can arise if the implementation fails partially or completely. Note that this is not an exhaustive or final list, but gives examples of chains of consequences that should be considered in the different project phases.

4.3.1. Implementation costs

The cost of implementing a measure can be incurred over a long period of time (Fig. 7). The measure must initially be planned for and designed, which entails costs for collecting data both in archives and in-field, analyzing data, creating models, running simulations, and producing blueprints for the contractor.

This is followed by the installation of the measure, maintenance, possible need for reinvestment, and daily operation. The installation is associated with internal project costs for material, equipment and machinery, fuel, transportation, labor, and time, as well as externalities, such as emissions from materials, operation, and transportation. The manufacturing of the material may lead to emissions. For example, cement used as a grouting agent or as a component in concrete used for lining has a large CO_2-footprint (Strømsvik, 2019). Transportation may cause increased travel and transportation time, increased emissions from traffic and decreased traffic safety in terms of both health risks and material damage due to traffic accidents. Some measures will increase the construction time of the facility, while some measures can be carried out without interfering with the progress of the project. Artificial recharge is a measure that can often be implemented in conjunction with the excavation of the facility while pre-grouting must be carried out before the excavation, which increases the excavation time. It is also important to remember that the installation includes both the installation of the measure itself, but also peripheral equipment, such as the installation of new utilities, e.g., pipes for water and cables for electricity needed for the operation of an artificial recharge well.

As to maintenance and potential reinvestment costs for the measure, they are not necessarily relevant for all types of measures. For artificial recharge facilities, maintenance is of the utmost importance since the facility must often be in operation for the same time as the life expectancy of the underground facility. Reinvestment may also be relevant to consider since recharge wells may become less effective with time due to, e.g., clogging (Bichara, 1986; Bouwer, 2002).

Daily operation may imply, e.g., costs for water and electricity used for artificial recharge wells. These costs constitute both internal project costs in the form of purchasing the water and electricity and potential land claims for the recharge facility, but also externalities, such as emissions from the electricity production.

Externalities may also arise from reinforcement measures to building foundations. During the period when the reinforcement measure is implemented, buildings may not be fully usable, which can cause lost revenues for businesses located within the building, increased noise pollution, and inconvenience to residents. Streets and roads adjacent to

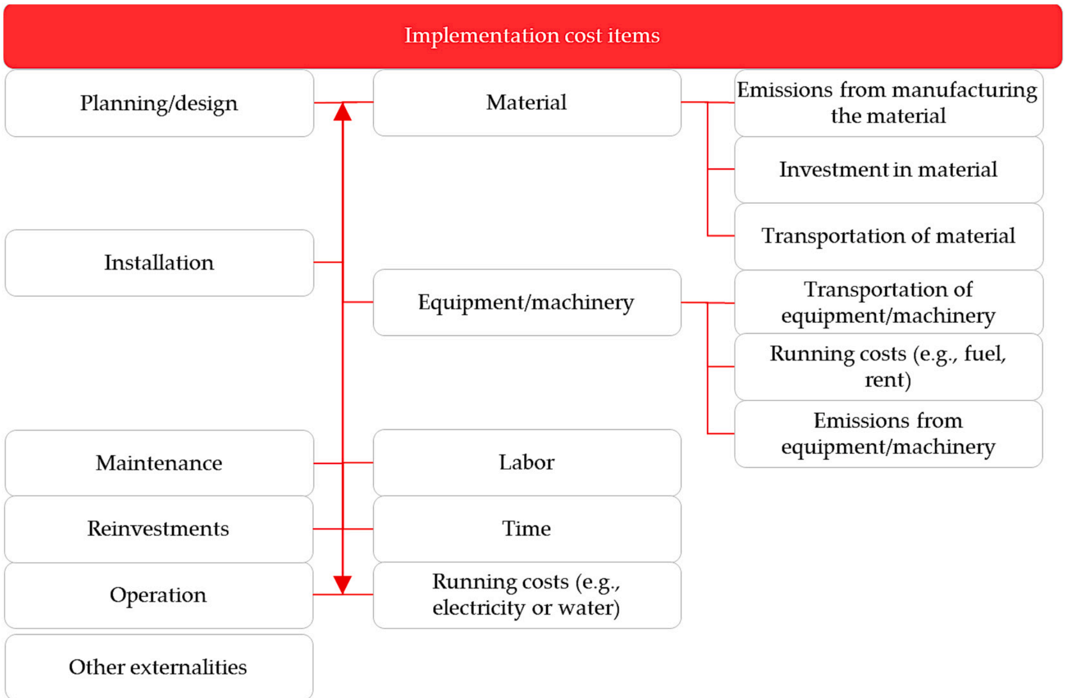

Fig. 7. Identified cost items of implementing a risk-mitigation measure. The Figure should be read from left to right and top to bottom. Arrows are present to highlight exceptions regarding direction or simply to guide the reader. The costs presented in the figure are generic and include some external project effects that can be internalized, i.e., be turned into internal project costs, via e.g., taxes.

the buildings may also be closed or restricted in use during construction, which may cause traffic delays and reduced accessibility.

4.3.2. Project risks

Due to the natural variability and our incomplete knowledge of the hydrogeological conditions of an underground project, the outcome of implementing a measure can never be certain (Merisalu et al., 2021). The project risks associated with this uncertainty therefore account for potentially considerable costs, which are important to consider on the cost side of a CBA of implementing risk-mitigation measures (Fig. 8).

A major project risk is the need for additional measures and their associated costs. In addition to increased implementation costs, the workload for employees within the project could increase because of sick leave and staff flight. Implementing additional measures takes time, which may imply delays and prolonged project delivery time. The delayed opening of the underground facility may cause substantial costs through the postponement of benefits gained from the facility. Delays are also associated with prolonged noise pollution, redirection of traffic, barrier effects, and impacts on schedules for other projects in the area (Adam et al., 2015; Gilchrist and Allouche, 2005). The cost of running the project and keeping the project organization will also be prolonged.

A larger than permitted groundwater leakage may also violate the legal permit, possibly causing fines or penalties. While fines are rather a transfer of money from the societal perspective of a CBA, additional legal processes involve resource use in terms of transaction costs, such as occupying the court, hiring legal representatives, and producing documents for a new legal hearing. A violation of the legal permit can also constitute a cause for the supervisory authority to stop production and

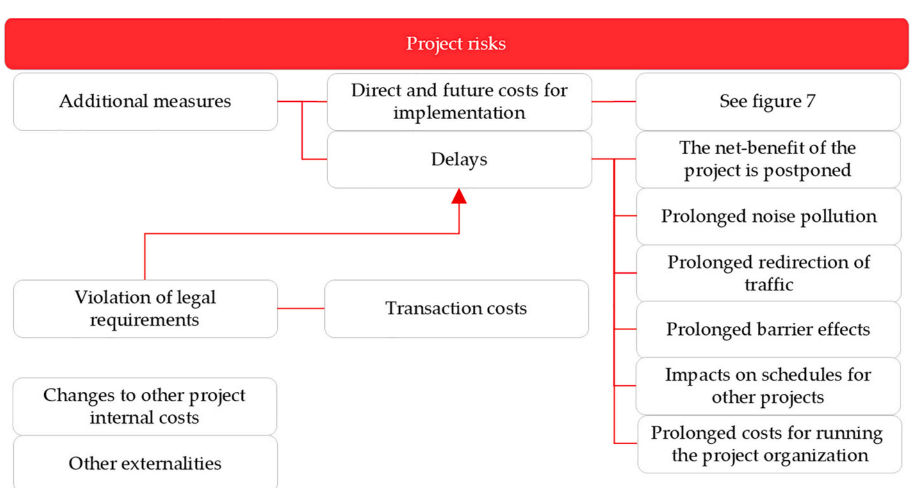

Fig. 8. Identified project risks arising from partly or completely failed implementation of risk-mitigation measures. The figure should be read from left to right and top to bottom. Arrows are present to highlight exceptions regarding direction or simply to guide the reader.

thus induce a delay.

Another example of the consequences of a failed measure are the unforeseen cost increases for managing and disposal of the inflowing water. The number of drains used in the facility may increase and the infrastructure, e.g., pipes and pumps, may be undersized and thus necessitate investment in new utilities and equipment. Such costs might be incurred by the project owner, but project risks also include unexpected or unforeseen externalities arising from failed implementation of the measure. One example of such an externality is leakage of chemicals from grouting agents into the environment (Bonacci et al., 2009; Vik et al., 2000; Weideborg et al., 2001). A watertight facility can also cause barrier effects since the impervious structure reduces the bulk transmissivity and hinders the natural groundwater flow, causing rise in water table upgradient and lowering downgradient (Pujades et al., 2012; Pujades et al., 2015). Another example is increased groundwater level in the vicinity of an artificial recharge well, which can result in floodings of, e.g., basements. The oxygen content of the groundwater may also increase due to artificial recharge, which can cause biodegradation of wood foundation piles (Elam and Björdal, 2023; Vatovec and Kelley, 2007).

4.4. Benefits and costs in the case studies

This section presents the identified cost and benefit items for the two case studies. Below, the use of the generic gross lists of hydrogeological risks and costs of risk-mitigation measures is demonstrated for the selected risk-mitigation strategy in the two case studies as described in Sections 3.2.1 and 3.2.2. The benefits (B_i) of risk-mitigation measures arise when risks in the reference alternative ($R_{tot\ ref}$) are reduced to $R_{tot\ i}$ thanks to the measures (see Eq. (2)). The costs of the measures (C_i) consist of implementation costs and costs associated with project risks compared to the reference alternative (see Eq. (4) and Section 4.3). A null alternative of not implementing any measure is used as the reference alternative in the two case studies. Note that the items presented in Tables 1-4 in Supplementary material 2 and in Tables 1 and 2 in Supplementary material 3 constitute the final items to be valued for a CBA (Eq. (5)). The generic information presented in Sections 4.1-4.3 is thus translated to site-specific items, i.e., they are only relevant for the case studies, but they illustrate the level of detail necessary for the final items to subsequently be valued.

The identified consequence items are presented in Tables 1-4 in Supplementary material 2 and the cost items are presented in Tables 1 and 2 in Supplementary material 3. The first two columns represent the generic primary and secondary risk events presented in the risk cascades for Tables 1-4 in Supplementary material 2, and the generic project phase in which cost items for measures will arise and the cost category for Tables 1 and 2 in Supplementary material 3. The third column presents the final items to be valued for a CBA, i.e., benefits in terms of avoidance or reduction of negative consequences because of risk-mitigation measures, and costs associated with the implementation of the measures.

Many items are relevant for both case studies, but some of them only apply to one. The relevant items for each case study are marked with the symbol ✓in the fourth and fifth columns. There is also extended versions of the tables in Supplementary material 4 and 5, which includes motivations for why an item is relevant or not. Also notice that the tables do not indicate the relative importance of the identified items nor do they indicate the probability and consequence of the item but rather an identification of a potential risk that should be analyzed in the following step constituting the risk analysis (see Section 2.1).

4.4.1. Benefit items

Both case studies have areas with sensitive clay that is prone to subsidence if there is **decreased pressure head** in the lower aquifer. This implies that a groundwater leakage may result in damage to the built environment, which in turn will result in costs for reparation as well as other consequences. Table 1 in Supplementary material 2 shows that most of the items to be valued are relevant for both case studies. However, the Westlink runs through a city center with dense urbanization, and the Eastlink runs through a rural area. This means that the Westlink is characterized by a much larger number of houses, utilities, and people living, working, or transiting to the area, and thus also a substantially larger magnitude of consequences associated with subsidence damage. In the Westlink, subsidence risks also pertain to businesses, such as commercial buildings, shops, cafés, and restaurants, and also historical buildings with subsidence sensitive foundations.

The risks associated with **decreased saturated thickness** are largely different for the two case studies (Table 2 in Supplementary material 2). The only risks they have in common are the reduced capacity of groundwater-based heat pumps due to the leakage-induced groundwater lowering. Compared to the Westlink, the Eastlink has many properties and households with private drinking water wells whose capacity may decrease due to groundwater lowering. There are also agricultural businesses within the Eastlink area that may be affected by the reduced capacity of these wells. The groundwater ecosystem in the Westlink will not be considerably affected by groundwater lowering since the groundwater system in the city is already heavily altered from its natural conditions. The groundwater ecosystem in the Eastlink is not well explored, but we assumed that groundwater lowering would affect habitats of the microbial communities and metazoan fauna. GDEs are only present for the Eastlink. A biodiversity survey was carried out as part of the EIA (STA, 2023b), which states that some of the groundwater-dependent wetlands constitute habitats for endangered and protected species, such as newts. The Getå stream is a habitat for, e.g., European river lamprey and brown trout. These species may be endangered if the baseflow of the stream is reduced.

An increased unsaturated zone could have an impact in both case studies. For the Westlink, the increased unsaturated zone can increase the biodegradation of the wooden foundations of buildings in the area. This could result in the need for reparation work on those buildings, as well as other risks associated with building damage. For the Eastlink, the increased purification of water percolating through the unsaturated zone could have a positive impact on the groundwater quality, which could benefit the users of private wells. This is an example of a benefit that could get lost if risk-mitigation measures are implemented. In both case studies, there may be archeological remnants that risk damage due to increased biodegradation.

The risks associated with **changed gradients** are mainly relevant for the Westlink (Table 3 in Supplementary material 2). Since part of the tunnel is built as an open shaft, groundwater leakage into the open shaft could result in piping due to the high gradient caused by the dewatered open pit. This increases the likelihood of retaining structure failure which, in turn, can cause injuries and delays for the project. Piping, and thus decreased stability of the soil, could also result in damage to the built environment. The risk of retaining structure failure is not relevant for the Eastlink, since the whole tunnel is built with drill and blast technology in the bedrock. Within the area of the Westlink, there is a risk of mobilizing old contaminants which, under Swedish law, would entail a responsibility for remediating the contaminant. For the Eastlink, the groundwater leakage-induced gradient towards the tunnel could transport water from the peatlands into the tunnel, which could cause increased corrosion to the tunnel construction, such as bolts.

The **risks in the underground facility** due to groundwater leakage are the same for both case studies (Table 4 in Supplementary material 2). Firstly, all inflowing water into the facility must be managed to secure dry working conditions and operation through the collection and disposal of water by, e.g., drains and pumps. During operation, an inflow of water can result in ice growth, which can trigger many risks such as damage to trains due to fallouts. However, most of these risks can be managed by increased maintenance. The maintenance of the tunnel must be carried out safely, and the tunnel must therefore be shut down during maintenance. This can result in increased travel time, increased emissions from traffic, and decreased traffic safety.

4.4.2. Cost items

The **implementation cost** items for risk-mitigation measures for the two case studies are mostly similar (Table 1 in Supplementary material 3). Both projects will use pre-grouting as their main sealing technique, which entails the same cost items. The Westlink tunnel also uses artificial recharge of groundwater as a measure to counteract groundwater drawdown. The Eastlink tunnel returns collected groundwater leakage water to the Getå stream to maintain a sustainable flow. The grouting, artificial recharge, and return of water to the stream involve similar cost items. However, pre-grouting is time consuming, and the implementation of this measure will increase the overall project time, while the other measures can be carried out without delaying the tunnel construction. Another difference is that maintenance and operation costs are only relevant for the artificial recharge and return of water. Notice that societal costs for emissions from material manufacturing, as well as from electricity production, are included in the table. However, in many countries, the market price for material and electricity includes emission taxes aimed at internalizing societal damage caused by emissions, and it might thus be necessary to make adjustments to avoid double counting (Johansson and Kriström, 2018).

The cost items that constitute **project risks** show some overlap and some variation between the two case studies (Table 2 in Supplementary material 3). Both case studies may face unforeseen costs associated with the implementation of additional risk-mitigation measures beyond the original plan. Both projects also face the risk of a delayed opening of the tunnel, which causes the net-benefit of the project (e.g., reduced travel time) to be postponed. However, some risks associated with delays, such as prolonged noise pollution, prolonged redirection of traffic, prolonged barrier effects, and impacts on other projects schedules, are only relevant for the Westlink, because this tunnel is partly built with an open shaft, causing major disturbances in central parts of Gothenburg.

Both case studies face the risk of violating legal requirements with respect to groundwater inflow, and the risk of increased costs for the management of the groundwater that flows into the tunnels. A risk for the Westlink is externalities caused by the artificial recharge wells, such as increased groundwater levels in the vicinity of the well and increased oxygen content in the groundwater, which can cause basement floodings, overflow of water in pedestrian lanes, and increased deterioration of wooden foundations. For the Eastlink, there is a risk that the water chemistry of the Getå stream will be impacted negatively by the returning water.

4.5. Next steps towards a complete CBA

The generic gross lists of risks and costs developed in this study are instrumental because they enable identification of what benefit and cost items are relevant for a specific case, and thus provide a qualitative CBA for that case. Such an identification involves defining benefit and cost items in a way that avoids double-counting, as well as providing a helpful overview of what data must be collected for the monetization of benefits and costs as a step towards a quantitative CBA in which the NPV of Eq. (5) can be computed. However, a quantitative CBA also requires quantitative input regarding the effects of groundwater drawdown, and how these effects can be reduced through risk-mitigation measures. That is, the causal relationships in the cascades, and thus the effects of the changes, must be quantified in reasonable detail for the specific case under study as a basis for monetization. In this section we discuss strategies and challenges associated with obtaining a complete CBA through the quantification of effects and monetization of benefits and costs.

4.5.1. Quantification of effects

One crucial step on the path towards a full quantitative CBA is the quantification of effects on objects at risk from leakage-induced groundwater drawdown. A quantification of these effects will often require a coupling of several models, each describing one part of the cause-effect chain constituting the cascade model. What approach to use for the various models is dependent on factors such as time and financial limitation, data availability, level of ambition, level of complexity of the system, and the overall circumstances and nature of the specific underground construction project. The models can be data driven or process-based numerical models and simulations, extrapolated data from, e.g., experimental studies, or based on expert elicitation (Merisalu et al., 2021). Below, we offer general quantification guidelines and reference examples from the literature on how effects could be quantified.

The first step in quantifying effects involves developing a model that can describe the initial event, which is the groundwater leakage into the construction. Focus here should be on determining the entry point of the groundwater and the magnitude of the groundwater leakage. This can be determined by, e.g., analytical or numerical models (see e.g., Dall'Alba et al. (2023), Luo et al. (2022), Farhadian and Nikvar-Hassani (2019), Butscher (2012), Font-Capó et al. (2011), Zhang et al. (2021), or Kitterød et al. (2000)). After the leakage model has been established, models that describe the changing properties of the groundwater must be developed; their focus is if, and with what magnitude, the groundwater level (and pressure head) in surrounding aquifers is affected by the groundwater leakage. There are several examples of approaches for quantifying the effects of drainage, see e.g., Gokdemir et al. (2022), Raposo et al. (2010), Molinero et al. (2002), and Cheng et al. (2019). The changes to functions, services and risks, as well as the value of the risks, must be described using different models that, as with the groundwater leakage and drawdown, are developed or adjusted for the site-specific conditions. If a groundwater drawdown can trigger changes in effective stress in subsidence sensitive soils, and thus damage the built environment, the models can, e.g., include changes to pore pressure and effective stress, damage and cost of damage (see, e.g., Haaf et al. (2024), Sundell et al. (2019) and Merisalu et al. (2023)). If a groundwater drawdown triggers a new cascade of changed baseflow in a recipient, the models must describe the relationship between groundwater levels and surface water flow (see, e.g., Flores et al. (2020) and Vincenzi et al. (2022)), as well as the ecosystem effects, such as changes to the habitat for certain species. The reduction of effects from implementing risk-mitigation must also be quantified. This can be determined using e.g., analytical or numerical models, see e.g., Li et al. (2024) and Katuwal et al. (2024). Quantification of project risks must also account for the human factor such as lack of communication or other factors that affect the organization and thus the construction work. Quantification of project risks is the subject of ongoing research.

Nature's inherent variability and our incomplete knowledge imply that uncertainties must always be taken into consideration when developing models. There are uncertainties regarding whether changes to properties, functions, and services will occur and if so, to what extent. In order to make sure that the models adequately capture the effects in the hydrogeological system, uncertainties should be accounted for in all of the models comprising the model-chain. There are also uncertainties regarding how the system being examined will change during the time horizon chosen for the CBA. The changes may affect both the conditions in the natural environment constituting the abiotic and biotic part of the hydrogeological system, and the social and economic systems. Climate parameters, such as precipitation and evapotranspiration, are examples of natural environmental parameters that may change during the chosen time horizon due to climate change, which in turn can have a negative impact on the objects at risk, see e.g., Kumar (2012), Collados-Lara et al. (2020), and van Engelenburg et al. (2018). A scenario analysis taking different climate scenarios into consideration could therefore improve the prognoses on hydrogeological system responses (Goderniaux et al., 2011). The social and economic systems, as well as their interaction with the natural system, may also face changes during the chosen time horizon, see e.g., Guaita García et al. (2020), and Hamilton et al. (2013). These changes may be difficult to predict and future scenarios defined for the scenario analysis must aim at turning unknown unknowns into analyzable known unknowns (Eriksson et al., 2022).

4.5.2. Monetization

Monetization implies the use of economic valuation methods to estimate total economic values, i.e., both use values and non-use values (TEEB, 2010). We refer to, e.g., Freeman et al. (2014) for comprehensive expositions, and illustrate various methods available by considering an example relevant to hydrogeological risks: a house owner that might incur costs to repair damage to the house as a consequence of groundwater drawdown. Such costs are often convenient to monetize because reparation services are available at markets and thus have a market price that can serve as a measure of economic value (possibly with some adjustments for, e.g., the presence of subsidies and taxes). However, the consequences could also be for non-market services not having a market price. This could be about a reduction in the owner's wellbeing through stress and discomfort, but another example could be the effect on freshwater ecosystems and associated ecological degradation and biodiversity loss, and thus the impact on the ecosystem services they provide. Such services are often not subject to trade in any market. For example, the house owner might be fond of angling in a watercourse nearby and therefore experience reduced wellbeing if the fish population in the watercourse is negatively affected by groundwater drawdown. This type of reduced wellbeing is also a cost to society, but it is a risk cost for which a market price might not be available.

Valuation methods have been developed within the field of environmental economics to enable monetization of non-market services: two main groups are revealed preference (RP) methods and stated preference (SP) methods. The former makes use of the fact that information about people's demand for non-market services might be at least partly captured by their behavior at related markets. For example, the house owner might be willing to purchase angling equipment, a fishing license, and fuel for travelling by car to the watercourse for the purpose of angling, and thus engage in market transactions related to angling activity. Data on such trade-offs are used in the travel cost method, an RP method which has been widely applied to value changes in recreational quality, though typically for travel to recreational sites that are situated farther rather than close to one's home. While RP methods rely on data on people's actual market behavior, SP methods, such as contingent valuation, are based on hypothetical market behavior by using surveys to pose questions directly to individuals about their willingness to make economic trade-offs (such as their willingness to pay) with respect to environmental change. SP methods make it possible to not only obtain information about use values, i.e., economic values related to people's use of the environment, but also about non-use values, such as existence values. For example, the house owner might also be willing to pay an amount to avoid the negative consequences of groundwater drawdown in another nearby watercourse. This could be out of concern about fish and other organisms in that watercourse, rather than an intent to visit or make use of the watercourse in any other way.

While collecting primary data by applying one or several of the valuation methods available is likely to be the most precise way of monetizing costs and benefits for the specific context for which a CBA is applied, it is common to use secondary data by transferring already existing value estimates, i.e., to apply so-called value transfer or benefit transfer (Johnston et al., 2021). In some cases, such transfers can be made based on standard values on, e.g., the social cost of noise and air emissions, the value of a statistical life, and the value of time savings, such as those established by the Swedish Transport Administration for use in CBAs of investment in transportation infrastructure in Sweden (STA, 2023a). Resources that simplify the search for suitable value transfer are databases such as the Ecosystem Services Valuation Database (Brander et al., 2021). For the specific case of geosystem services and ecosystem services whose provision is affected by changes in subsurface structures and processes, such as those affected by groundwater drawdown, a systematic literature review by (Frisk et al., 2024) indicates a substantial need for new primary valuation studies.

Finally, it should be noted that workshop participants identified consequences that might be important to consider for decision-makers, but present challenges in their inclusion in a CBA for theoretical and/or practical reasons. The participants pointed out, for example, that delays in tunnel projects might result in reduced trust in responsible authorities among the general public. The extra cost implied by such delays could also result in potentially important, but hard-to-predict, knock-on effects, such as budget cuts for other projects with the same project owner, which in turn could result in lost net benefits from these projects. Such potential items were not included in the gross lists above.

5. Discussion

5.1. The usability of the cascade model and the identified risk cascades

Despite its practical usability in real-world projects, the cascade model has limitations that need to be considered: i) the causal relationship between the levels in the cascade is unidirectional, while in reality there might be feedback loops within the model between the different levels; ii) the model is lacking in mediating the complex, nonlinear, and dynamic connections in the ecological systems; and iii) it implies that humans and the social and economic systems are separate from nature, even though humans as biological creatures are part of nature (e.g., La Notte et al. (2019) and Costanza et al. (2017)).

The first limitation of the cascade model has been a major focus in our development of the hydrogeological risk cascades. The cascades that are presented in this paper do not constitute linear models that can only go from one starting property to a final value. Instead, some of the cascades can initiate feedback loops that initiate new cascades. These cascades can be directly and intuitively linked to the groundwater system. An example of such a direct feedback loop is the risk of negative changes to the property baseflow in the recipient because of decreased saturated thickness (storage) in the feeding aquifer, which subsequently can result in a decreased amount of water being available for GDEs. These kinds of feedback loops, which constitute changes to a major property that most often is considered an important feature of the hydrogeological setting, have been included in the cascade. However, the cascades can also generate feedback loops that are only remotely related to groundwater drawdown. One example of such a cascade is the changed regulation of global climate in GDEs resulting from reduced carbon storage. An increase of greenhouse gases can give rise to numerous cascades that relate to topics such as invasive species (Hellmann et al., 2008) or productivity in agriculture (Ciscar et al., 2011; Olesen and Bindi, 2002). However, the presented cascades would be unmanageable if all such feedback loops were to be included (if even practically possible). The user of the presented cascades must therefore be attentive to identify additional feedback loops beyond those presented but which may be relevant.

The second limitation of the cascade model relates to its simplification of nature. However, even though the cascade model and its entities of boxes representing the properties, functions, and services in a unidirectional model appear to be simple, the level of complexity that the model can capture is to some extent limited by the user's knowledge of the system being described and analyzed, and the user's ability to integrate this knowledge into the model. We wish to argue that the model and its entities of boxes, together with the lines that describe the interactions and dependencies, should be seen as a conceptual framework or an empty shell which can be filled with different levels of complexity.

The third limitation relates to the separation of humans and our social and economic systems from nature. The cascade model, and in general the concept of ecosystem services, is anthropocentric, as it focuses on the instrumental values of nature through their contribution to human wellbeing (Bennett et al., 2015; Haines-Young and Potschin, 2010). A main critique towards the concept of ecosystem services has been that it excludes the intrinsic value of nature (McCauley, 2006; Redford and Adams, 2009). While this critique is valid, it calls for complementary types of analyses rather than dismissing the ecosystem service concept, which is an important tool for increasing awareness on the importance of functioning ecosystems, as well seeing ourselves as an integrated part of nature (Summers et al., 2012). Recent work by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) suggests a solution to this by applying a combination of values-centered approaches for valuation that is fair to people and nature including inter- and intragenerational equity (Brondizio et al., 2019; Pascual et al., 2023). In this paper, we put instrumental value on nature by using the cascade model to identify risks to humans from leakage-induced groundwater impacts. However, the cascade model is divided into two parts: the environment, and the social and economic systems. By using the whole model, changes in groundwater conditions will result in consequences that will influence human wellbeing, which in turn can be quantified in monetary terms. However, this way of expressing the value of nature in instrumental terms does not contradict that it also has an intrinsic value (Soulé, 1985). This relates to the fact that the environmental parts of the cascade chain can be used independently to identify effects on the environment. Thus, the cascade model's way of analyzing the dynamic interactions of properties and functions can be a valuable tool for understanding the effects that a leakage-induced groundwater impact can have on the hydrogeological system. This understanding can be achieved without including the social and economic systems, potentially shedding light on nature's intrinsic value (Cole et al., 2021).

5.2. Application for risk identification and translation into benefit items

The risk cascades presented in this paper and the associated text that provides more detailed examples of hydrogeological risks form a tool for identifying risks that could be relevant to consider when constructing below the groundwater table. One major advantage of the arrangement of the generic cascades is that it enables usage in various types of hydrogeological settings and is thus not restricted to Swedish conditions. Another advantage is that a basic conceptual understanding of the hydrogeological setting is enough to enable a first identification of which cascades are relevant to consider from the early stages of an underground project. However, the cascades themselves do not provide all the information needed to identify the risks for specific cases. It's important to be aware that the cascades are just models whose output quality depends on the information that is input. This implies that the cascades must always be used with local information to be relevant. As an example, the gross lists and the associated text state that the habitat for aquatic organisms can deteriorate due to groundwater lowering. However, which species may be affected is not stated, since it depends on the local conditions of that system.

To enable an evaluation of risk-mitigation measures in a CBA, the risks need to be translated into benefit items that can be valued. To clarify, the cascades can identify the risk of damage to buildings due to subsidence. The associated benefit items are about the consequences of the damage, such as subsequent reparation costs. The purpose of presenting the result for the identified cost and benefit items for the two case studies was to offer guidance and an example of how the identified risks from generic risk cascades (Sections 4.1, 4.2, 4.3) can be translated into cost and benefit items as inputs to a CBA (Section 4.4). Since the case studies constitute two different hydrogeological settings with different objects at risk, we also provide guidelines on what cost and benefit items are relevant to consider depending on the local conditions. The gross list of cost items (Section 4.3) helps the user structure the costs that implementing a risk-mitigation measure can entail. The list presents the costs that must be considered for any risk-mitigation measure in different project phases. This reduces the risk of missing any cost items because they occur in the planning or operation phase rather than when the measure is implemented. As a final remark on usability, the identified cost and benefits items can provide the basis for distributional analysis and address equity issues (see Section 5.4).

5.3. Approaches to risk valuation

Recall from Section 2.2 that Eqs. (1) and (2) imply an expected damage approach to CBA. This is attractive from a practical point of view, which is evident from the fact that this approach is often applied in practical CBA (Boardman et al., 2018). However, it has some important limitations. To explain this, recall from Section 4.5.2 the example with an individual owning a house which might be affected by groundwater drawdown because of subsidence. If affected, the owner incurs costs to repair associated damage, and these costs are one component of the variable K_F in Eq. (1). Implementation of measures imply a reduced damage risk for the house owner. Following the expected damage approach suggested by Eqs. (1) and (2), the valuation of the reduced risk is accomplished by the CBA analyst by using the best available scientific knowledge for estimating the probabilities in Eq. (1), and then using Eq. (2) to arrive at the benefits of implementing measures as the reduction in expected damage costs.

This setting, which is also referred to as risk valuation *ex post* (Freeman et al., 2014; Shaw and Woodward, 2008), is associated with at least three issues. First, if the damage costs are limited to costs of reparation, these costs do not include reductions in the owner's wellbeing due to stress and discomfort when experiencing property damage. A more complete estimate of damage costs would therefore be obtained through valuation methods investigating the owner's willingness to pay to avoid damage by applying one or several of the valuation methods mentioned in Section 4.5.2. Second, such a willingness to pay would indeed reflect the owner's preferences with respect to the consequences of groundwater leakage (i.e., with respect to avoiding damage), but it does not recognize preferences with respect to probabilities, i.e., with respect to risk reduction as a whole. This is a limitation from a consumer sovereignty perspective, i.e., the principle in standard welfare economics that advises that individual preferences should be respected when assessing what is beneficial to society and what is not (Johansson and Kriström, 2018). Risk valuation *ex ante* through the so-called option price approach adheres to this principle by investigating, prior to knowing which consequence will actually occur, what people are willing to pay for a risk-mitigation measure to be implemented (Shaw and Woodward, 2008; (Freeman et al., 2014). Third, the relationship between such an option price and the expected value of avoiding damage is complex, but the former is likely to exceed the latter in a case with a risk averse house owner whose wellbeing depends on income, and with measures which also contribute to reduce income risk (Boardman et al., 2018).

The presence of these issues indicates that expected damage costs might differ from the total economic value of risk reduction. In some cases, expected damage costs are likely to underestimate the total economic value if they are limited to the costs of reparation. A basic step for avoiding underestimation is therefore to ensure that reductions to wellbeing due to stress and discomfort are identified whenever relevant, as was done for the case studies in Section 4.4. Such an identification implies that even if monetization of wellbeing impact cannot be accomplished due to lack of data, the impact will still be considered qualitatively in the CBA, and thus not be forgotten or overlooked. A more advanced step would also be to consider for what identified risks people can be expected to have a considerable degree of risk aversion. This could indicate which risks are especially important when seeking estimates for the total value of risk reduction.

Such estimates can be obtained through applying the RP and SP methods introduced in Section 4.5.2. RP methods, such as investigating people's behavior at markets for risk-mitigation equipment, are one option (smoke alarms and other fire safety products are a typical example, see e.g., Jaldell, 2023), but they do not necessarily reveal what risk magnitude is actually perceived by an individual when the market transaction was carried out. However, applying SP methods involves communicating a valuation scenario in which a particular risk change in described; this poses challenges in how probabilities and changes in probabilities can be effectively communicated to survey respondents (Logar and Brouwer, 2017), and may require substantial effort for survey preparation in terms of time and budget. While there are plenty of RP and SP estimation efforts for various types of risk, such estimation is often challenging, and usable results might not be available for the specific risk context under investigation in a CBA. This is one reason why the expected damage approach followed in this paper is often reasonable to apply in practice.

5.4. Equity issues

The impression given so far by this paper might be that the estimation of NPV gives the end result of a complete CBA. However, while NPV gives information on a project's social profitability, this does not say whether the project's outcome is equitable. The NPV criterion (also referred to as the Kaldor-Hicks criterion) for social profitability suggests that a project having a positive NPV implies a *potential* to make every affected individual better off through redistributions among winners and losers, and that a project having a positive NPV therefore should be carried out (Boardman et al., 2018). This argument is quite similar to viewing profits in a firm as something that potentially could benefit every shareholder and employee through dividends and remunerations. However, does the potential implied by a positive NPV mean that the project would improve social wellbeing? Not necessarily (Hammitt, 2013), and one main aspect of this question is how benefits and costs are distributed among individuals and groups and society, i.e., who are the winners and who are the losers?

In general, a project having a positive NPV is likely to be controversial from an equity point of view if the winners are already well-off individuals and the losers belong to vulnerable groups in society, especially when considering that the marginal utility of income is likely to decrease (Nurmi and Ahtiainen, 2018). This suggests that an equity analysis, i.e., investigating and identifying how benefits and costs are distributed among different groups in society, is an important supplement to a CBA. According to Martens (2011), the substance of an equity analysis must answer three questions: 1) which costs and benefits should be the focus of an equity analysis?; 2) how should members of society be distinguished into groups?; and 3) what constitutes a fair distribution? How these questions are answered is highly dependent on the nature of the project. However, in many cases, a distributional analysis is helpful for answering questions 1 and 2, i.e., different benefit and cost items are broken down for relevant groups in society (Martens, 2009). While income groups are a conventional basis for a distributional analysis, other groups might also be relevant depending on what type of project is being assessed. As an example, children can be more sensitive to air pollution compared to adults, calling for a grouping of members in society based on age. In contrast, households owning a car could benefit from travel time savings from a new road, calling for a grouping of members in society based on car ownership. The information gained through a distributional analysis is in turn instrumental for a discussion about whether the project's outcome can be viewed as equitable or not (question 3). Note that the equity analysis could serve as a basis for identifying potential win-win opportunities (Cecot, 2023).

Equity also has an intergenerational dimension, which in a CBA context has primarily been discussed through the impact of the discount rate when computing NPV. However, intergenerational aspects also include whether future generations have different preferences than present generations, or a different financial ability to pay for the expenses that implementing a project will entail in the future (Lind, 1995). We refer here to the extensive literature on these issues, including the suggestions of applying a decreasing discount rate over the studied time horizon for taking the interest of future generations sufficiently into account (e.g., Arrow et al. (2014), Dasgupta (2021), and Johansson and Kriström (2016, 2018)).

6. Conclusions

The aim of this paper is to present a method for identifying relevant cost and benefit items to provide the basis for conducting a CBA of hydrogeological risk-mitigation measures in underground construction. By using the principles of the cascade model, workshops, and literature review, a method for identifying relevant items for a CBA could be developed.

The main conclusions of this study are:

- The principles and structure of the cascade model are applicable for identifying hydrogeological risks induced by groundwater leakage into underground constructions.
- The gross lists of costs associated with implementing risk-mitigation measures, as well as project risks, ensure that expenses associated with the measures in all phases of the project are included in the CBA.
- The two case studies demonstrate that the risk cascades are universal enough to be usable for both rural and urban hydrogeological environments.
- The identified risk cascades and the gross lists of implementation costs and project risks, together with local knowledge, form the basis for a comprehensive identification of cost and benefit items associated with implementing risk-mitigation measures, which in turn enables a qualitative CBA.
- The qualitative CBA presented in this paper provides examples on how the hydrogeological risks, implementation costs, and project risks can be translated into case-specific benefits and costs, and thus indicates what should be monetized to enable a complete quantitative CBA which avoids double counting.
- Challenges associated with obtaining a complete quantitative CBA and strategies to handle these have been discussed and presented.
- Given the potentially large economic consequences to society from groundwater leakage to underground constructions, the structured identification and subsequent CBA of mitigation measures presented here is an important contribution to a more efficient use of society's limited resources.

CRediT authorship contribution statement

Johanna Merisalu: Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Tore Söderqvist:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Yevheniya Volchko:** Writing – review & editing, Conceptualization. **Jonas Sundell:** Writing – review & editing, Funding acquisition. **Lars Rosén:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

Appendix A. Supplementary data

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Data availability

Not relevant for this study.

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