Risk Assessment of Groundwater Drawdown in Subsidence Sensitive Areas

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Department of Architecture and Civil Engineering
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CHALMERS UNIVERSITY OF TECHNOLOGY
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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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"*Uncertainty is an uncomfortable position. But certainty is an absurd one*"

-Voltaire

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Cover:
Risk for land subsidence due to groundwater drawdown, expressed as a function of probability of subsidence and economic consequences.

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ABSTRACT

Groundwater leakage into sub-surface constructions can result in drawdown, subsidence in compressible materials, and costly damage to buildings and installations. When planning for sub-surface constructions where there is a risk for land subsidence due to groundwater drawdown, the need for safety measures must be carefully evaluated and managed. Since the sub-surface consists of heterogeneous and anisotropic materials, which cannot be fully investigated in all aspects, decisions regarding safety measures must be taken under uncertainty. In this thesis, a generic framework is presented on how to assess the risk of groundwater drawdown-induced subsidence (Paper I). As specific tools for modelling uncertainties in the groundwater drawdown – subsidence – damage chain, a method for probabilistic modelling of bedrock levels and soil stratification (Paper II) and a method for probabilistic modelling of ground subsidence to a large spatial extent (Paper III) are presented. These are combined with a probabilistic groundwater model and cost functions to calculate the economic risks of subsidence damage between different design alternatives (Paper IV). Finally, a novel method for economic valuation of hydrogeological information is presented in Paper V. The methods presented can distinguish between low and high-risk areas, identify the alternative with the highest net benefit compared to a reference alternative, and estimate the expected benefit of additional information. The methods have been demonstrated to provide useful support for decision-making and communication tools when assessing the risk of large-scale groundwater drawdown-induced subsidence in different infrastructure projects in Sweden.

Keywords: groundwater leakage, groundwater drawdown, urban hydrogeology, subsidence, risk assessment, probabilistic, uncertainty quantification, spatial variability, inverse modelling, economic valuation, economic valuation, cost-benefit analysis, value of information analysis.

This thesis contains material that has been published previously in the author's licentiate thesis: Sundell, J. (2016). *Risk Estimation of Groundwater Drawdown in Subsidence Sensitive Areas*. (Licentiate thesis), Chalmers University of Technology, Gothenburg.

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following publications, referred to by Roman numerals:

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I. Sundell, J., Rosén, L., Norberg, T., Wladis, D., & Alén, C. (2015b). *A framework for risk assessment of groundwater drawdown induced subsidence.* Paper presented at the International Symposium on Geotechnical Safety and Risk (ISGSR2015), Rotterdam, the Netherlands. http://ebooks.iospress.nl/book/geotechnical-safety-and-risk-v

II. Sundell, J., Rosén, L., Norberg, T., & Haaf, E. (2015a). *A probabilistic approach to soil layer and bedrock-level modelling for risk assessment of groundwater drawdown induced land subsidence.* Engineering Geology. doi: http://dx.doi.org/10.1016/j.enggeo.2015.11.006

III. Sundell, J., Haaf, E., Norberg, T., Alén, C., Karlsson, M., & Rosén, L. (2017). *Risk Mapping of Groundwater-Drawdown-Induced Land Subsidence in Heterogeneous Soils on Large Areas.* Risk Analysis. doi: http://dx.doi.org/10.1111/risa.12890

IV. Sundell, J., Haaf, E., Tornborg, J., & Rosén, L. (2018). *Comprehensive risk assessment of groundwater drawdown-induced subsidence.* Submitted manuscript.

V. Sundell, J., Norberg, T., Haaf, E., & Rosén, L. (2018). *Economic valuation of hydrogeological information in managing groundwater drawdown.* Provisionally accepted by Hydrogeology Journal following revisions.

Division of work between the authors

In publication I, Sundell, Rosén and Norberg devised the structure of the five modules. Wladis contributed to the formulation of the groundwater module and Alén to the subsidence module. Rosén suggested the organization of the risk assessment process and described the modules for risk estimation and risk evaluation. Sundell formulated the description of the cause-effect chain and the first three modules and was the main author of the paper.

In publication II, all the authors formulated the objective of the paper. Norberg devised the mathematical foundation for converting empirical distributions into normal z-scores. Haaf implemented the stochastic model and contributed to the formulations of the chapters. Sundell elaborated on the concept of the modelling process, performed the kriging interpolations, and was the main author of the paper.

In publication III, Sundell and Rosén formulated the objectives of the paper. Haaf implemented the stochastic model, performed the sensitivity analysis, and contributed to the formulations in all the chapters. Alén and Karlsson contributed with expert knowledge in subsidence modelling. Sundell developed the method, performed the ANOVA analysis, defined the probability density functions of the parameters, elaborated on the model process, and was the main author of the paper.

In publication IV, Sundell and Rosén formulated the objectives of the paper. Haaf implemented the stochastic model combination and contributed to the formulations in all the chapters. Tornborg contributed with expert knowledge in subsidence modelling. Sundell developed the overall method, performed the kriging interpolations, the ANOVA, and the groundwater modelling, defined the cost functions, and was the main author of the paper.

In publication V, Sundell and Rosén formulated the objectives of the paper. Sundell performed the inverse probabilistic groundwater modelling. Haaf processed the results from the groundwater modelling and contributed to the formulations in all chapters. Norberg and Sundell devised the foundation for the pre-posterior analysis. Norberg performed the calculations in the pre-posterior analysis and the bootstrap function. Sundell was the main author of the paper.

Other work and publications not appended

Sundell, J. (2016). *Risk Estimation of Groundwater Drawdown in Subsidence Sensitive Areas.* (Licentiate of Engineering), Chalmers University of Technology, Gothenburg. https://research.chalmers.se/publication/236827

Sundell, J., Rosén, L., Haaf, E., Alén, C., & Karlsson, M. (2015). *A Probabilistic Approach for Calculation of Land Subsidence on a Macro-Scale.* Paper presented at the International Conference on Creep and Deformation Characteristics in Geomaterials, Gothenburg, Sweden. doi: 10.13140/RG.2.1.3904.6483

Sundell, J., Rosén, L. Wladis, D., Fransson, Å., Ericsson L.O. (2015). *Assessing the risk of groundwater drawdown induced land subsidence (Abstract)*, Poster presented at IAH International Congress, AQUA2015, Rome, Italy.

Sundell, J., & Rosén, L. (2015). *Riskhantering vid grundvattensänkning i sättningskänsliga områden – Risk management of groundwater drawdown in subsidence sensitive areas (Extended abstract in Swedish).* Oral presentation at Grundvattendagarna 2015 – Grundvatten och samhällsplanering (Groundwater days – groundwater and planning), Gothenburg, Sweden.

Sundell, J. (2016) *Risk management of groundwater drawdown in subsidence sensitive areas.* Oral presentation at KTH Dome of Vision, Stockholm.

Sundell, J., & Rosén, L. (2016). *City-Link Stockholm; an integrated hydrogeological and geotechnical risk assessment (Extended abstract).* Oral presentation at the 25th Seminar on URBAN HYDROGEOLOGY, Trondheim, Norway.

Sundell, J., Rosén, L. (2016) *Risk assessment of groundwater drawdown in subsidence sensitive areas (Abstract)* Poster presented at SRA 2016 Meeting in San Diego, USA.

Sundell, J. (2017) *En perfekt modell är inte att lita på – You can't trust a perfect model (Abstract in Swedish).* Oral presentations at Bergmekanikdagen (Rock mechanic day), Stockholm, and, at Hydrologidagarna (Hydrology days), Gothenburg.

Sundell, J., & Rosén, L. (2017). *Vad är värdet av hydrogeologisk information (in Swedish) – What is the value of hydrogeological information?(Abstract)* Oral presentation at Grundvattendagarna (Groundwater days), Uppsala.

Sundell, J., Rosén, L., Haaf, E. (2017) *Metodbeskrivning av probabilistisk modell för berg-, jordlager- och grundvattennivåer – Method description for a probabilistic model of bedrock-, soil stratification- and groundwater head levels (Report in Swedish)* Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg.

Sundell, J., Rosén, L., Haaf, E. (2018) *Invers probabilistisk modellering av förändrade grundvattennivåer – Inverse probabilistic modelling of changes in groundwater heads (Report in Swedish)* Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg.

Sundell, J., Rosén, L., Haaf, E. , Tornborg, J. (2018) *Metodbeskrivning av probabilistisk marksättningsmodell vid grundvattensänkning – Method description of a probabilistic groundwater-drawdown induced subsidence model (Report in Swedish)* Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg.

Sundell, J., Rosén, L., Haaf, E. (2018) *Metodbeskrivning av riskberäkning och riskvärdering av marksättning vid grundvattensänkning – Method description of risk calculation and risk valuation of groundwater drawdown induced land subsidence (Report in Swedish)* Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg.

Sundell, J., & Rosén, L. (2018). *Vad är värdet av hydrogeologisk information – What is the value of hydrogeological information? (Conference paper in Swedish)* Oral presentation at The Foundation Day (Grundläggningsdagen), Stockholm

Sundell, J., Rosén, L., Haaf, E., Tornborg, J. (2018) *A comprehensive method for risk assessment of groundwater drawdown induced land subsidence (Abstract)*. Oral presentation at Groundwater and Life: Science and Technology into Action - IAH International Congress 2018, Daejeon, Korea.

Sundell, J., Rosén, L., Haaf, E., Tornborg, J. (2018) *Riskbedömning vid grundvattensänkning i sättningskänsliga områden – Fallstudie Varbergstunneln – Risk assessment of groundwater drawdowns in subsidence sensitive areas – Case study of the Varberg Tunnel (in Swedish).* Report manuscript. Rock Engineering Research Foundation, Stockholm.

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Jonas Sundell
Gothenburg, September 2018

1 INTRODUCTION

1.1 Background

Increased global urbanization generates a demand for improved infrastructure services such as roads, railways, sewage and electric power. Since these services compete with space for buildings and recreation, infrastructure services are being increasingly located beneath the land surface in tunnels (see e.g. Huggenberger & Epting, 2011).

In areas with compressible soil deposits, such as clay and peat, groundwater leakage into an underground facility that causes groundwater drawdown can lead to land subsidence and costly damage to buildings and constructions. Groundwater drawdown-induced land subsidence has led to severe consequences in, e.g. Shanghai (Xue et al., 2005), Mexico City (Ortega-Guerrero et al., 1999), Bangkok (Phien-wej et al., 2006), Hanoi (Dang et al., 2014), Las Vegas (Burbey, 2002), Los Angeles (Bryan et al., 2018) and the Scandinavian cities of Stockholm, Gothenburg and Oslo (Olofsson, 1994; Karlsrud, 1999). Subsidence due to groundwater drawdown is linked to the United Nations Sustainable Development Goal "Securing Sustainable Water for All" with regard to reducing the risk of water-related disasters. In addition, UNESCO's definition of water security includes protection of life and property against water-related hazards such as subsidence (UNESCO-IHP, 2012).

Compared with constructions above ground, complexity and uncertainties in sub-surface projects can be substantially higher since these are constructed in poorly known materials that have been formed and impacted by complex geological and anthropogenic processes (Lundman, 2011). Since groundwater drawdown from a sub-surface construction can affect very large areas (square kilometres) if the hydrogeological conditions are unfavourable (e.g. Burbey, 2002; Huang et al., 2012), methods are needed to assess the uncertain and heterogeneous conditions on this scale.

To reduce the risk of damage, further investigations or safety measures can be undertaken. Additional investigations can reduce uncertainties while safety measures can increase redundancy in the system. Investigations include geotechnical and hydrogeological sampling and testing as well as inspection of constructions at risk. When deciding on the need for additional investigations, there can be a trade-off between the benefits of increased knowledge and the cost of new information. Safety measures include the sealing and grouting of tunnels, stabilization of buildings and their foundations, and controlled artificial infiltration of water to maintain groundwater heads. Deciding which safety measures to implement also involves a trade-off between the benefits of reduced risks and the costs. Since the conditions are uncertain when deciding on actions regarding additional investigations and safety measures, the implementation of these actions are associated with two major project risks:

1. *The risk of <u>not taking</u> action <u>when necessary</u> in the light of harmful groundwater drawdown and subsidence.* If the drawdown causes damage, the project owner is, under Swedish law (Swedish Environmental Code 1998:808 Ch. 16), responsible for the costs and consequences of the damage. In addition to direct costs for the project owner, indirect negative consequences for victims and society as a whole could also arise.
2. *The risk of <u>taking</u> action <u>when it is not necessary</u> in the light of harmful groundwater drawdown and subsidence.* This risk is associated with unnecessary costs for measures and investigations that are not needed.

These two project risks create a need for relevant decision support with regard to necessary safety measures and additional investigations. Decision support of this nature must acknowledge and deal with the different sources of uncertainty in the system. Uncertainty can be defined as any deviation from the unachievable ideal of complete deterministic knowledge (Walker et al., 2003). There are different sources of uncertainty, including: (1) Context and framing of the boundaries and the initial conditions of the system to be modelled; (2) Input data and external forces that drive the model; (3) Model structure uncertainty in the conceptual model due to incomplete understanding and simplified descriptions of processes; (4) Parameter uncertainty; (5) Technical model uncertainty deriving from numerical approximations, resolution in space and time, and bugs in the software (Refsgaard et al., 2007). The nature of uncertainty is commonly categorized into aleatory uncertainty (due to inherent variability) and epistemic uncertainty (due to imperfect knowledge). Epistemic uncertainty can be reduced through improved knowledge, whereas aleatory uncertainty cannot be reduced. There are different strategies to deal with the uncertainties, such as ignoring them, choosing conservative scenarios, using the observational method, or quantifying them (Christian, 2004).

For a comprehensive risk assessment that recognizes the different sources and types of uncertainty in the system, the whole cause-effect chain of groundwater drawdown-induced subsidence needs to be understood (see Figure 1). This chain is initiated with leakage of groundwater into a sub-surface construction in bedrock (1a) or soil (1b). It continues with a reduction of groundwater piezometric heads in confined aquifers due to the leakage (2). The drawdown reduces pore pressure in compressible deposits (3) and causes subsidence (4). The extent of the subsidence damage (5) depends on the vulnerability of the constructions founded on the compressible deposits. The consequences can at least be represented in part by the cost (6) associated with the damage. In this process, the consequences are determined by the interaction between geotechnical and hydrogeological conditions and the vulnerability of the constructions at risk. To cause damage, several conditions need to be fulfilled jointly, i.e. groundwater drawdown affects the pore pressure in compressible soils below constructions that are vulnerable to subsidence. The cause and effect chain thus implies that several processes in the system need to fail to cause the system to fail. In the cause-effect chain for groundwater drawdown-induced subsidence, available information and its characteristics can vary between the different parts. This variability means that it can be difficult to use the same strategy to deal with all sources of uncertainty. Instead, a combination of several methods is needed to take proper account of uncertainties in a comprehensive risk assessment.

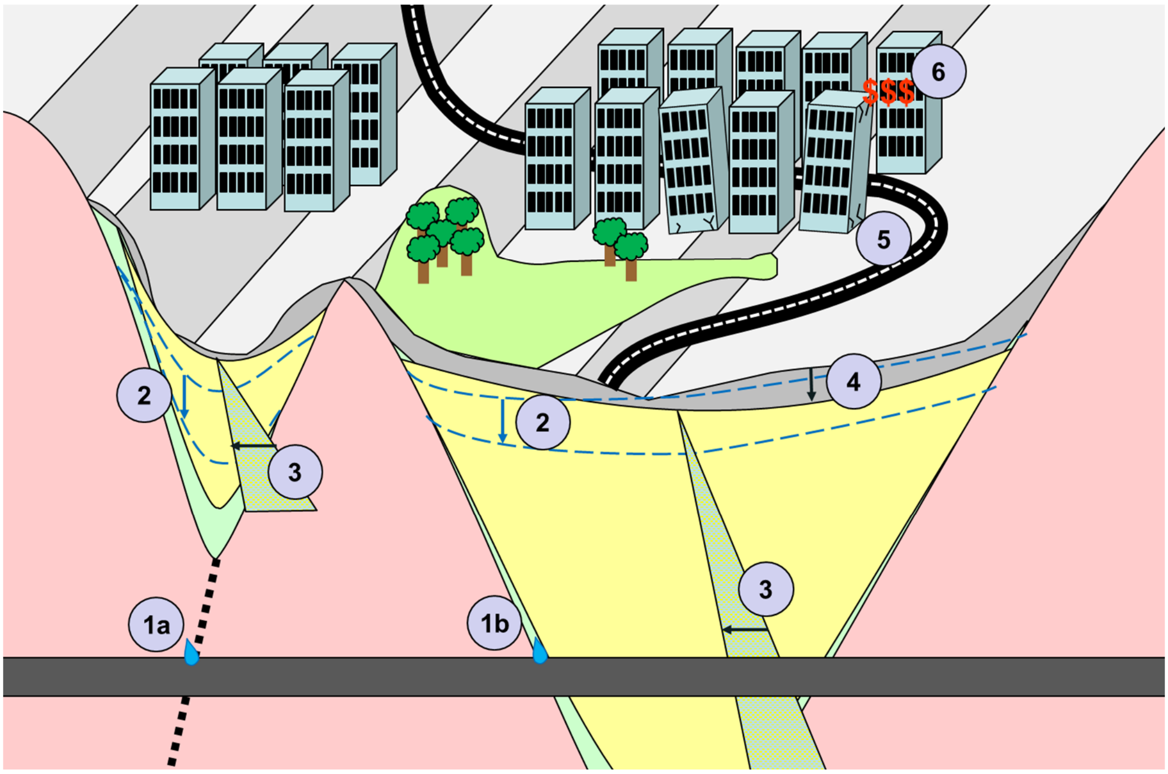

Figure 1 The different processes in the chain for groundwater drawdown-induced subsidence damage, caused by a tunnel (the dark grey horizontal structure). Materials: pink: bedrock; green: coarse-grained glacial and glacio-fluvial deposits; yellow: soft clay; grey: coarse-grained filling material. The broken line at 1a illustrates a fracture zone in the bedrock.

Several studies cover the relationship between groundwater drawdown and ground subsidence but focus on evaluation of historical observations and not risk assessments of future events (e.g. Galloway & Burbey, 2011; Modoni et al., 2013; Shen et al., 2013; Zhang & Burbey, 2016). In studies of future events, uncertainties in the predictions are often neglected (e.g. Yan & Burbey, 2008; de Lange et al., 2012; Hung et al., 2012; Bakr, 2015). In addition to studies that consider the whole system, current research on future behaviour in the system is largely directed at individual parts of the cause-effect chain, with or without uncertainty estimation. Examples include methodologies for testing the hydromechanical properties of rock fractures (Thörn & Fransson, 2015), design concepts for evaluation of grouting to avoid leakage (Butrón et al., 2010), frameworks for groundwater modelling (LeGrand & Rosén, 2002), probabilistic studies of groundwater drawdown and subsidence but without taking into account heterogeneous conditions (Persson, 2007) and subsidence modelling (Sällfors, 1975; Alén, 1998; Olsson, 2013; Sivasithamparam et al., 2015).

As in academic studies, professional approaches to address groundwater drawdown-induced subsidence damage in planned infrastructure projects in Sweden are by tradition quite widely distributed between hydrogeology, geotechnics and environmental impact assessment. The main issues are addressed, but since clear links are lacking between the different parts, it is difficult to acquire an overview of the risk of incurring damage costs in order to communicate and assess the results (e.g. Bergab, 2004; Aqualog, 2007; Berzell, 2011; Borgblad & Bengtsson, 2012; Berzell & Dehkordi, 2017). Nevertheless, comprehensive risk assessment methods have been developed for use in other fields, including management of contaminated sites and water supplies (Lindhe et al., 2009; Göransson et al., 2014; Brinkhoff et al., 2015). In these fields, methods that are also available for cost benefit analysis (CBA) of safety measures (Lindhe et al., 2011; Malm et al., 2015; Söderqvist et al., 2015) and Value of Information Analysis (VOIA) for prioritization of additional investigations (Back et al., 2007; Zetterlund, 2014). The methods applied in these fields are to a large extent based on generic CBA descriptions (Boardman et al., 2011) and risk analysis (ISO, 2009; Aven, 2012).

1.2 Aim and specific objectives

The overall aim of this thesis is to

> *Develop a comprehensive framework, including methods that can be applied in practice, for risk assessment of groundwater drawdown-induced subsidence in infrastructure projects, taking into account the entire chain of events from groundwater leakage to land subsidence and damage costs. The methods included should collectively serve as a useful source of decision support for implementation of cost-efficient safety measures.*

To meet the overall aim, there are four specific objectives:

1. *Develop and apply a method for probabilistic modelling of bedrock levels and soil stratification.*
2. *Develop and apply a method for probabilistic modelling of subsidence on a large spatial scale (km^2) that utilizes the bedrock and soil stratification model.*
3. *Develop and apply a procedure that links geological, hydrogeological and subsidence models to a comprehensive risk assessment model, facilitating cost-benefit analysis of safety measures.*
4. *Develop and apply a method for value of information analysis of additional hydrogeological investigations when managing groundwater drawdown.*

In the research project presented in this thesis, the purpose is to develop useful tools for decision support that embrace the whole cause–effect chain and its uncertainties. This is achieved by applying interdisciplinary approaches that combine the fields of hydrogeology in bedrock and soil, geotechnical engineering and risk assessment. This project provides novel methodologies to better predict the risk of harmful subsidence caused by groundwater drainage. More accurate risk predictions are believed to make decision-making more efficient, reduce costs associated with subsidence problems, and improve communication of the risks to stakeholders, authorities and contractors.

1.3 Scope of work

The overall aim of this thesis is achieved through theoretical studies and method development. The methods are applied, tested and evaluated in two case studies in the Swedish cities of Stockholm and Varberg. In Stockholm, case studies deal with probabilistic soil and bedrock modelling (Publication II), probabilistic subsidence modelling on a large spatial scale (Publication III), and value of information analysis of additional hydrogeological investigations (Publication V). The Stockholm case studies are applied to the City Link Tunnel, which is a planned utility tunnel in bedrock for power lines. In Varberg, the methods in Publications II and III are combined with a probabilistic model of groundwater leakage and drawdown and a cost function for subsidence damage. These combined models calculate the economic risk related to different design alternatives for a planned railway tunnel (Publication IV). The usefulness of the methods is demonstrated in each publication.

Figure 2 illustrates how the publications relate to each other. Publication I provides a framework for risk management of the cause-effect chain for groundwater drawdown-induced subsidence. This publication relates to the overall aim. The specific methods included in the framework are presented in Publications II-V.

Publication II provides a method for modelling the basic geometric structure of bedrock and soil layers for analysing risks in the cause-effect chain. This is necessary to allow additional groundwater and subsidence modules to be added when estimating the risks in the chain. The City Link Tunnel case study has provided data for the model. Publication II relates to the first specific objective.

Publication III introduces a method for spatial mapping of the groundwater drawdown-induced subsidence risk. In the publication, subsidence magnitudes resulting from certain groundwater drawdown magnitudes are modelled probabilistically. The method estimates risks in the third (pore pressure) and the fourth (subsidence) part of the chain. The model in Publication II provides soil and bedrock geometry for subsidence simulations. The City Link case study provided data. Publication III relates to the second specific objective.

In Publication IV, a method is introduced for comprehensive risk assessment with cost-benefit analysis (CBA) of different design alternatives. In the publication, leakage of groundwater and groundwater drawdown is modelled using an inverse probabilistic (calibration-constrained Monte Carlo simulation) model combined with the methods for soil and bedrock stratification (Publication II) and subsidence (Publication III), together with a cost function for subsidence damage. The Varberg case study provided data. Publication IV relates to all parts of the cause-effect chain and to the third specific objective.

In Publication V, a procedure is presented for economic valuation using VOIA of additional hydrogeological information when managing groundwater drawdown. VOIA is a CBA where the cost of collecting new information is compared with the expected benefits of a reduced risk of making an erroneous decision relative to a reference alternative. In the publication, leakage of groundwater and groundwater drawdown is modelled using an inverse probabilistic model, where the model for bedrock and soil stratification (Publication II) provides a geometrical model. The subsidence modelling in Publication III defines areas of unacceptable groundwater drawdown. With a novel algorithm that combines the result of the inverse groundwater modelling with VOIA, the benefits of expected uncertainty reduction with additional information is calculated. The City Link case study provided the data. Publication V relates to the fourth specific objective.

This thesis introduces the cause-effect chain between groundwater leakage and subsidence damage costs in Section 2. The theoretical background of each part in the chain and applied methods are presented in Sections 3-7. An overview of the publications and their main findings is presented in Section 8. A discussion and recommendations for future research are presented in Section 9, and the main findings of the thesis are presented in Section 10.

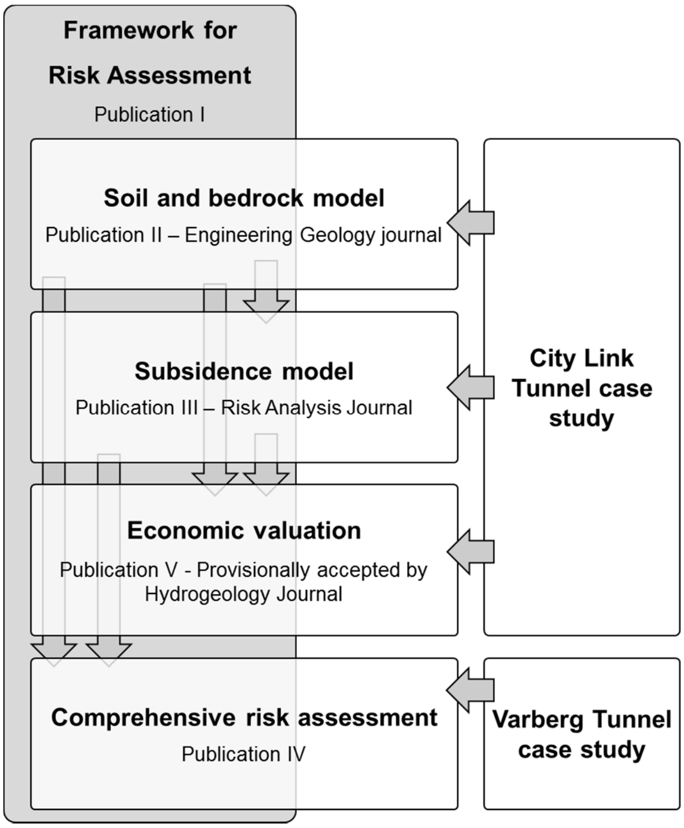

Figure 2 An illustration of how the publications relate to each other and the case studies.

1.4 Limitations

To address the entire cause-effect chain of groundwater drawdown subsidence damage costs, a combination of several methods is required. The framework and methods presented can be seen as a toolbox where the parts can be adapted, improved and replaced according to the needs of the situation. Although the entire cause-effect chain is embraced in this thesis, some parts are addressed in greater depth. The following limitations need to be highlighted:

- The focus has been on a procedure for probabilistic soil and bedrock modelling, statistical analysis of parameter data, and probabilistic inverse calibration of groundwater models combined with CBA and VOIA. Less developed parts include the applied subsidence model (does not take into account 3D and creep), building response and the effects of buildings on the stress situation, together with the cost functions for subsidence damage. Nevertheless, the methods can serve as useful decision support at an early stage in the planning since the main responses of the system are captured.
- Only parameter uncertainties, analysed using statistical methods and probabilistic inverse modelling techniques, have been addressed. These methods are limited by conceptual assumptions, model structures and available input data. This means that the outcome of the models also needs to be reviewed with regard to these limitations, which it is suggested should be done in future research. Since a future scenario is modelled, model validation with the outcome in question is impossible. The soil and bedrock model is validated by means of data splitting, whilst the soundness of the other models is addressed in the publications appended to this thesis.
- The methods presented are developed for an early stage risk assessment of large areas (km^2). When a smaller scale is of interest and detailed information is available for a specific part of the chain, conventional methods can be used. This includes e.g. inflow into individual fracture zones, subsidence calculations for an individual construction, and detailed estimations of damage costs for specific objects.
- Since all the case study locations are in Sweden, the methods that have been developed are based on a typical information setting in Swedish infrastructure projects. This implies that a Swedish standard procedure for an oedometer test (CRS – Constant Rate of Strain), together with a subsequent subsidence calculation, are used instead of methods that are more recognized internationally (e.g. incremental loading). Although the method is demonstrated using CRS-evaluated samples, the principle is applicable to incrementally loaded samples using the compression index method.
- The methods have been developed for a steady state situation. One exception is in Publication IV, where the transient consolidation process is considered.

2 THE CAUSE-EFFECT CHAIN

From an economic perspective, the magnitude of consequences due to groundwater drawdown-induced subsidence is determined by the interaction between hydrogeological conditions in soil and bedrock, the geotechnical conditions in the soft soil, the vulnerability to subsidence of the constructions at risk, and the cost to compensate for the resulting damage. In this cause-effect chain (Figure 1 and Figure 3), several conditions need to occur jointly to cause damage. This chain is initiated by groundwater leakage into the construction (Figure 3, No. 1). For a construction in bedrock, the hydraulic conductivity in the fractures and the success of sealing determine the inflow rate, see e.g. Thörn (2015). Depending on the magnitude of the leakage and its duration, the hydrogeological conditions in soil determine the extent of the groundwater drawdown and the reduction in pore pressure (Nos. 2 and 3). If the water balance conditions are beneficial, e.g. with the presence of an esker with high hydraulic conductivity, storage and groundwater recharge, these conditions can compensate for a relatively high inflow. The water balance conditions can also be unbeneficial, and even a relatively small inflow results in an excessive groundwater drawdown, e.g. in a confined layer of glacial till. Together with the extent of the groundwater drawdown, the geomechanical properties in the soil materials govern the subsidence magnitude (No. 4). The severity of the subsidence damage is determined by the vulnerability of affected constructions (No. 5). Finally, the cost to compensate for the damage determines the economic risk (No. 6). Consequently, the cause and effect chain implies that several processes in the system need to fail in order to cause system failure.

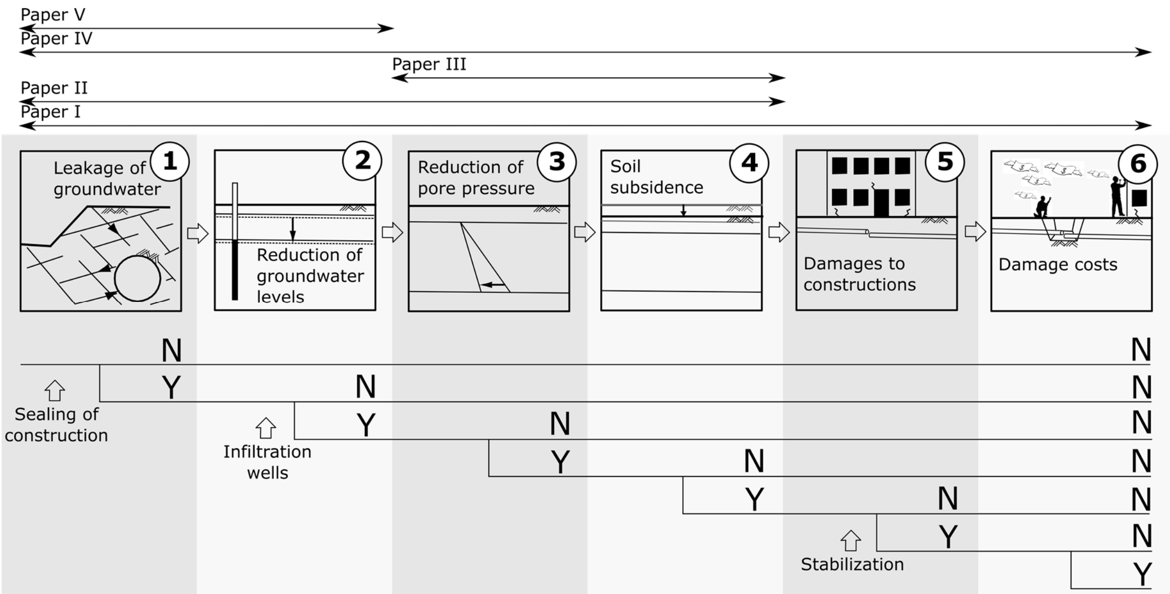

Figure 3 The cause-effect chain for groundwater drawdown induced subsidence damage, an event tree describing the possible chains of events and the contents of appended papers. Yes (Y) and No (N) means that an event occurs/does not occur respectively. Three different types of safety measures are illustrated at different points in the cause-effect chain (arrows).

The cause-effect chain can be described using an event tree (bottom part in Figure 3). In this event tree, leakage into the construction is the initiating event and the different parts are safety systems that all need to fail to give rise to damage costs (system failure). Safety measures to treat risks are possible to implement in different parts of the chain, including sealing of the construction, infiltration of water to maintain groundwater levels, and stabilization of buildings (arrows in Figure 3). The event tree is limited by the cause-effect chain not being a binary process. It is quite continuous and the extent of the damage costs is determined by the interaction of the different parts. How critical these processes are varies between projects and sites, which implies that the full range of aspects of the cause-effect chain need to be understood properly for each individual sub-surface construction project.

Although the preconditions might vary between projects, the information setting in urban infrastructure projects in Sweden is often similar. For major infrastructure projects it is common that the geotechnical and hydrogeological properties are evaluated based on an extensive investigation programme. In addition, borehole logs describing soil stratigraphy from previous construction projects are often easily obtainable, both in Sweden and elsewhere (de Rienzo et al., 2008; Marache et al., 2009; Velasco et al., 2013). Although large numbers of investigations are available, only a very small fraction of the soil volume that will be affected by the construction can be observed. Broms (1980) suggests that 1 ppm of the volume can be investigated. In the Stockholm and Varberg case studies, borehole logs with soil stratification data have a density of about 450 logs/km^2. Samples and tests describing geotechnical and hydrogeological properties are less frequent, with around six groundwater observation wells per km^2 and two locations with piston samples of clay per km^2. In both case studies, general information on the foundations of most buildings is available from archive inventories.

As the information varies in character between each part of the chain, different methods for uncertainty estimation need to be combined for a comprehensive risk assessment. The methods presented in this thesis are adapted to the above-described information setting by combining different approaches for uncertainty estimation of the data types mentioned. In Paper I, the whole cause-effect chain is recognized in the suggested framework (uppermost part in Figure 3). The method for probabilistic modelling of soil and bedrock levels in Paper II indirectly covers parts 1-4 since a geometrical model is necessary to model groundwater flow and subsidence. The subsidence model in Paper III addresses parts 3-4 through a combination of the soil stratification model in Paper II, interpolation of groundwater data, and a statistical analysis of compression data from piston samples. Paper IV addresses all parts of the chain through a combination of inverse probabilistic groundwater modelling techniques, the methods in Papers II and III, and calculation of subsidence damage costs. Paper V is focused on parts 1-2, although the acceptance criterion for groundwater drawdown is defined from Paper III (parts 3-4) and the failure cost is partly based on part 6.

3 RISK ASSESSMENT OF THE CAUSE-EFFECT CHAIN

There are different definitions of risk including "a combination of probability and consequence of a hazardous event" (Kaplan, 1991), and effect (positive and/or negative deviation from the expected) of uncertainty regarding objectives (ISO, 2009). In this thesis, risk is described in economic terms as a continuous function where the economic risk of land subsidence, R_s, is stated in the form of a combination of the economic cost, C_s, and the probability of damage of a certain degree, f_s:

$$R_s = \int C_s f_s ds, \qquad (1).$$

Risk management is defined as "coordinated activities to direct and control an organisation with regard to risk" (ISO, 2009). These activities can include both preventive and preparative measures. Risk management (Figure 4) includes risk assessment (risk identification, risk analysis, and risk evaluation) and risk treatment (ISO, 2009). The risk assessment is initiated by an underlying decision problem where the context is established. Based on the decision problem, suitable methods and tools should be used in the risk assessment. This assessment needs to address spatial and temporal issues together with different geological conditions, vulnerability of constructions, and associated damage costs, as well as stakeholder preferences in the area affected by the tunnel construction.

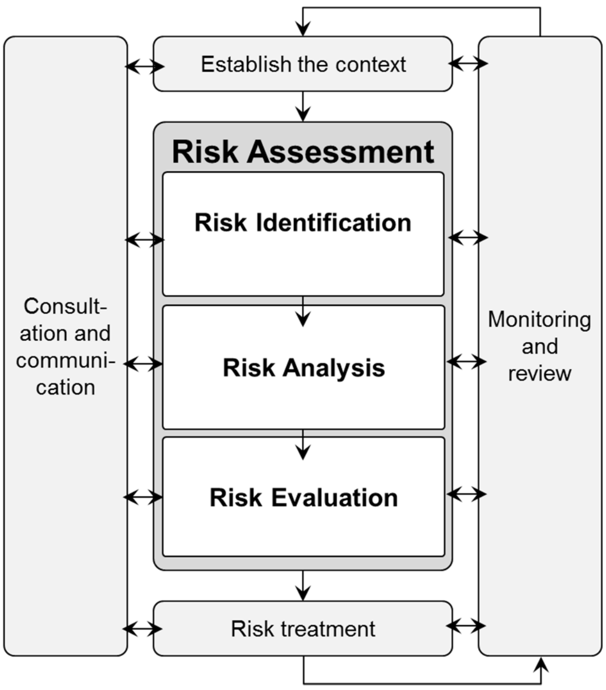

Figure 4 The risk management process (ISO, 2009).

3.1 Stakeholder consultation and communication

Since stakeholders are affected by the consequences, their preferences regarding risk and safety measures need to be considered through continuous consultation and communication (Figure 4). Stakeholder values (goals, criteria and preferences) affect the decision problem, the risk assessment and the subsequent decision regarding risk treatment. For risks related to groundwater drawdown and subsidence, stakeholders include the project owner, the contractor, authorities, building owners, interest groups and tenants (companies and individuals). It is likely that the risk perception is considerably different between stakeholders potentially affected by damage and the contractor. This means that early involvement and transparent communication with different stakeholder groups is of great importance (Saltelli & Funtowicz, 2014). A key to successful risk communication is two-way communication between experts and stakeholders where both sides have something valid to contribute and each side respects the insights of the other (Slovic, 1987; ISO, 2009).

In Sweden, limits for groundwater drainage for sub-surface projects are decided in the environmental court (Swedish Environmental Code 1998:808 Chap. 11). As a basis for the legal process, the project owner needs to describe the extent and possible consequences of a planned groundwater drawdown. This description is then reviewed by stakeholders before the court regulates the conditions for affecting the groundwater. The project owner is responsible for groundwater damage-related costs and consequences. Unlike many other legal situations, there is an inverse burden of proof. This means that the accused party (the project owner) must provide evidence of the circumstances. (Swedish Environmental Code 1998:808 Chap. 2).

3.2 Decision problem – establishment of context

There are different alternatives for safety measures and information collection, such as alternative designs, sealing procedures, infiltration of water, and additional sampling and investigations. The decision problem is to identify the best of these options, given selected decision criteria, such as the highest net benefit, the least costly, the lowest risk, or the most sustainable alternative (Burgman, 2005). By maximizing the net benefit as the primary decision criterion, the risk of subsidence damage as a function of probability of occurrence and damage cost needs to be estimated for each design alternative (equation 1). The reduced economic risk from a design alternative compared with a reference alternative and its investment cost, results in a net benefit (see Section 3.5). In addition to an estimation of this net benefit, the value of additional information should be addressed. Additional information can reduce uncertainties, which can change both the risk estimation and which alternative to opt for (see e.g. Back et al., 2007; Zetterlund, 2014). In a VOIA perspective, only information which has the potential to change the preferred alternative is considered worthwhile (see Section 3.6).

3.3 Risk analysis

In the initial phase of risk analysis, the scope is defined based on the concerns, assumptions and required output to support decision-making in order to address the problem (Rosén et al., 2010). The scope should include a definition and a description of the system (cause-effect chain in Figure 3). At this stage, a team of people who are familiar with both the system and risk analysis should be assigned (Rosén et al., 2010).

After defining the scope, the hazards and their interrelationships are identified (for example using an event tree as presented in Figure 3). After this step, the risks are estimated in terms of probabilities and consequences (equation 1). The methods presented in this thesis express risk in quantitative terms (see e.g.Bedford & Cooke, 2001) although qualitative descriptors could also be used depending on the purpose (ISO, 2009).

3.4 Risk evaluation

In the next step, the risk evaluation, the output of the risk analysis is evaluated in terms of support when choosing between alternatives. The risk analysis may conclude that a permanent groundwater leak (hazard) in a design alternative can cause damage costs of SEK 2 million (consequence) with a probability of 0.05. Although this conclusion provides an overview of the general risk of subsidence damage, the decision whether this is acceptable and how it relates to other design alternatives is very limited. Risk evaluation can be performed in different ways. One approach is to define *tolerability criteria*, reflecting acceptance levels of affected stakeholders and regulations from authorities (Burgman, 2005). An example of a tolerability criterion is that it is accepted that a certain level of subsidence (e.g. 2 cm) could occur at a certain level of probability (e.g. a maximum of 0.05). Tolerability criteria can also be defined on other levels in the chain, for example by assigning acceptable damage or damage costs to the buildings. As far as the author is aware, quantitative tolerability criteria for damage costs have not been applied to Swedish infrastructure projects. Instead, tolerability criteria for leakage, groundwater drawdown, subsidence (one of these or a combination) and monitoring are typically defined. Examples include: leakage should not be greater than a certain amount for the West Link railway tunnel in Gothenburg (case M 638-16, Land and Environmental Court, 2018); groundwater levels are permitted to be lowered to certain defined levels in the Bypass Stockholm highway project (case M 3346-11, Land and Environmental Court, 2014); and subsidence should be less than 20 mm for some defined buildings in the City Tunnel railway project in Malmö, Sweden (case M 487-04, Land and Environmental Court of Appeal, 2004). Although tolerability criteria are defined for levels in the cause-effect chain other than the last level (subsidence damage costs), they should be based on an estimation of the actual consequence. This means that tolerability criteria can be based on the risk (cost of subsidence damage) but defined for intermediate parameters of the risk (leakage, groundwater drawdown or subsidence magnitude).

When an acceptance tolerability criterion is used, the safety measure that best meets the criterion should be chosen based on a *decision analysis of alternatives*. One approach for this analysis would be to rank design alternatives in terms of e.g. how well they fulfil the tolerability criteria, and their risks and costs. Another approach is through cost-effectiveness, where the safety measure that can meet the tolerability criteria at the lowest cost should be recommended (McNulty et al., 1997; Levin & McEwan, 2000). If a cost-benefit analysis (CBA) is used instead, the expected risk reduction compared with a reference alternative, i.e. a benefit, is compared with the cost for implementing the measure (with or without considering tolerability criteria).

3.5 Decision analysis of alternatives using CBA

In a CBA, in the definitions of f_s and C_s, R_s is calculated for each alternative, i. With one alternative defined as the reference alternative ($i = 0$), the benefit of an alternative is given by:

$$B_i = R_0 - R_i \, , \qquad (2).$$

Each alternative has an investment cost, c_i. The net benefit of an alternative is given by:

$$\Phi_i = B_i - c_i. \qquad (3)$$

If benefits and costs change over time, equation 3 can be modified so that a Net Present Value (NPV) is calculated:

$$\Phi_i = \sum_{t=0}^{T} \frac{1}{(1+r)^t} [B_i(t) - c_i(t)], \qquad (4)$$

where T is the time horizon [for years t] and r is the discount rate (see e.g. calculation of costs for infiltration water in Publication V).

Subsequently, the best alternative is the alternative with the greatest value:

$$\Phi_{prior} = \max(\Phi_i). \qquad (5)$$

The criterion for CBA is the maximum net benefit (Burgman, 2005; Hanley & Barbier, 2009), which can result in a recommendation to accept extensive damage if this turns out to be the most profitable alternative (without tolerability criteria). In practice, successful risk evaluation has to comply with norms and regulations in society (with tolerability criteria), resulting in a CBA constrained by respect for existing norms, e.g. risk tolerability criteria. Such a ”constrained CBA approach” can recommend a more expensive alternative if this is justified by its benefits and NPV, compared to a cost-effectiveness analysis approach, which recommends the alternative that meets defined goals (e.g. a tolerable risk level) at the lowest cost (Levin & McEwan, 2000; Kriström & Bergman, 2014).

3.6 Decision analysis of the need for additional information using VOIA

The need for additional information can be estimated using Value of Information Analysis (VOIA). VOIA is a CBA where the cost of collecting new information is compared with the expected benefit of the reduced risk of making an erroneous decision relative to a reference alternative (see e.g.Back et al., 2007; Zetterlund, 2014). The result of the VOIA is – from an economic perspective – a selection of the most appropriate information collection alternatives (IT-Corporation, 1997; Yokota

& Thompson, 2004). This evaluation is initiated using a *prior analysis,* which is a CBA based on the current level of available information (equations 2-5). In the *preposterior analysis*, the expected information gain from a planned investigation is evaluated by comparing the monetary benefit of the expected information with the cost of realizing the investigation (Freeze et al., 1992). The expected value of information, *EVI,* is calculated as the difference between the pre-posterior and the prior present values:

$$\mathrm{EVI} = \Phi_{pre-posterior} - \Phi_{prior}. \qquad (6)$$

In these calculations, value of information is only present if the investigation has the potential to change the decision on which alternative to recommend. EVI does not consider the data collection cost, c_p. To do so, the Expected Net Value (ENV) is calculated:

$$\mathrm{ENV} = \mathrm{EVI} - \mathrm{c}_p. \qquad (7)$$

Based on the result of the VOIA, additional investigations or the best prior alternative is recommended.

3.7 Monitoring and review

The outcome of the risk assessment provides decision support on which alternative to implement. This means that the outcome of the risk assessment is a recommendation and not the decision itself. The recommendation is reviewed by the decision-maker (project owner based on the regulations decided in the land and environmental court) together with the stakeholders. The risk assessment is not just a matter of technical understanding of a system where science provides the means for rational decision-making, see Weinberg (1972). Although quantitative probabilistic methods are used, bias in sampling and laboratory evaluation, different model conceptualizations, or alternative numerical models are typically not quantified. Since the reason for using a model is a lack of full access to the phenomena of interest, it is the responsibility of the modeller to demonstrate the degree of representativeness of the real system and to delineate the limits of that representation (Oreskes et al., 1994). This demonstration can be very difficult for a future scenario, which can only be validated after it has occurred. Decisions regarding risk-reduction measures obviously need to be made before damage occurs. If decisions are to be made regarding these measures, it is important to evaluate whether the process representation is sufficiently detailed to be useful for predicting the dominant modes of response in the system (Beven, 2007). Nevertheless, the cause-effect chain is a transient process, meaning that damage does not occur immediately after groundwater leakage. This can create a time period for implementation of safety measures before critical levels in the cause-effect chain are reached (which justifies the transient subsidence model in Paper IV) as suggested by the observational method (Peck, 1969; Zetterlund et al., 2008; Spross & Larsson, 2014). This method includes a preliminary design, a monitoring plan with acceptance criteria, and an action plan that is put into operation if acceptance is exceeded (Spross & Johansson, 2017). If the outcome of the risk assessment indicates significant uncertainties regarding the extent of the damage, together with a sufficient time period to implement safety measures before damage occurs, the observational method can be a good strategy.

As mentioned in Section 1.1, the same strategy cannot be applied to all sources of uncertainty. In risk assessment in practice, uncertainties can rarely be quantified based on existing data only. They therefore need to be addressed to some degree by means of expert opinions and judgements. Since some uncertainties cannot be evaluated quantitatively, it is important to reflect on the quality of evidence (van der Sluijs et al., 2008). A review of Swedish hydrogeological consultancy reports on facilities constructed in bedrock found that data, methods and assumptions were often unclear and uncertainties were often not described sufficiently (Werner et al., 2012). If information is difficult to access and understand for stakeholders, communication fails. Instead, transparent communication of uncertainties and the potential consequences should be aimed for (Saltelli & Funtowicz, 2014). Communicating uncertainties should not be mistaken for insufficient control. What it actually means is that the project owner is prepared to take action on a number of possible scenarios. A revision of the risk assessment should see beyond the result and add considerations regarding the knowledge or lack of knowledge, as well as issues not captured (Aven, 2016). Tools for structured approaches in this revision include the NUSAP (Numeral, Unit, Spread, Assessment, and Pedigree) system (Funtowicz & Ravetz, 1990, 1993; Refsgaard et al., 2005; Van der Sluijs et al., 2005; Refsgaard et al., 2007; van der Sluijs et al., 2008), and the uncertainty matrix (Walker et al., 2003). In addition to a quantitative analysis covered by the first three letters of the NUSAP acronym, a qualitative assessment of the reliability of the quantitative estimation is introduced together with a pedigree matrix of qualitative estimations of the methodological and epistemological limitations in the underlying knowledge base (Van der Sluijs et al., 2005). In an uncertainty matrix, sources of uncertainty are described qualitatively with regard to their level (statistical, scenario, recognized ignorance) and nature (epistemic and aleatory) (Walker et al., 2003).

The arrows in Figure 4 indicate the exchange of information between the different steps and communication with stakeholders. It is important to stress that the result of a risk assessment is not a product that is completed once and then ignored. Risk assessment and decision-making should be a continuous and iterative process that is updated when new information becomes available and when preconditions change (Burgman, 2005; ISO, 2009; Rosén et al., 2010).

4 GEOLOGICAL STRATIFICATION

To understand and describe the characteristics and the interactions of the hydrogeological and the geomechanical system, a sound understanding of the geological stratification geometry is necessary. This understanding needs to be based on the geological and anthropogenic processes forming and impacting on the bedrock and soil within the modelled area. A geological model provides information on the stratigraphy between boreholes and helps to understand spatial variation of geological formations. If the geological model is parameterized, it can be combined with a hydrogeological and/or geomechanical model for spatial modelling of groundwater flow and subsidence respectively.

4.1 Generalization of geological conditions

The typical geological setting in glaciogeological regions subject to glacio-marine depositions have in this work been simplified to three continuous soil layers, which are present where the bedrock surface forms valleys as shown in Figure 1. This geological setting is representative of the case study sites and many urban areas in Sweden, including Stockholm and Gothenburg. The presented methods in this thesis are applicable when this simplification to three continuous layers can be made. In this geological setting, glacial till and glaciofluvial esker material dominate the bottommost coarse-grained material, where glacial till is deposited directly on the bedrock and can be found outcropping at locations with high bedrock altitudes, as well as on the sides of the sediment-filled valleys. At certain locations in the valleys, the glacial till is washed away due to glaciofluvial erosion and glaciofluvial sediments are deposited directly on the bedrock. Glaciofluvial deposits can also be present on top of the glacial till in the case of incomplete out-washing. Above the coarse-grained layer, clay has been sedimented in low energy (deep and calm water) depositional environments. The topmost coarse-grained layer typically consists of abrasion sediments or filling material. The bedrock geology in Sweden is dominated by Precambrian crystalline igneous and metamorphic bedrock, which is also the setting in the case studies. Nevertheless, the general approach to geological and hydrogeological modelling in this thesis is assumed to also be valid for other rock settings. Except for the location of dominant fracture zones and variability of hydrogeological properties (see Section 5), geological modelling of different bedrock types within the Precambrian domain is outside the scope of this thesis.

4.2 Information setting in urban areas

Soil stratification and bedrock levels can be interpreted from the large number of borehole logs that typically exist in an urban area. The interpretation is often made indirectly from other measurements, such as Cone Penetration Tests (CPT), static sounding, and soil/rock drilling, thus creating uncertainties. In addition to uncertainties at the sampling locations, uncertainties also arise between the samples. Although a refinement of the simplification to three soil layers with additional material categories would be desirable, the vast majority of the borehole data in the case studies is not sufficiently detailed to classify this distinction. Using geophysical investigation methods, it is possible to cover the area of interest with higher data density. Since the case studies are based on the typical information setting in Swedish cities and geophysical investigations are often not included, the presented methods are limited to borehole logs. Nevertheless, it would be possible to combine interpretations from geophysical investigations with borehole logs in a geological model, see e.g. Andersen et al. (2018). When considering geophysical methods, ambiguities and uncertainties account must be taken of local conditions and the presence of electromagnetic noise from sub-surface installations that can disturb the result (Kearey et al., 2013).

4.3 Stratification modelling using kriging

Several structured interpolation procedures for building geological models, e.g. Asa et al. (2012), Bourgine et al. (2006), Chung and Rogers (2012) and the method presented in Publication II, are based on the geostatistical kriging method (Matheron, 1963). The basis for kriging is the variogram (Figure 5), which describes the relationship between distance and variability of a variable in space. Kriging provides a probabilistic approach by which a weighted average and an uncertainty estimation are calculated at each interpolation point. In Publication II, a kriging-based probabilistic bedrock level and three-layered soil stratification model, which takes into account dependencies between the different layers, is presented. The theoretical background to kriging is given in this section.

The primary advantage of kriging is its ability to interpolate values from known data points and provide estimates of the uncertainty at all locations in the model domain. Kriging is commonly used to obtain an estimate with minimum error variance. When modelling using kriging, a variogram is used to estimate the spatial correlation structure between the data. The variogram is also used in an interpolation process when values at unsampled locations are estimated by weighting the values of neighbouring data points. Moreover, a variogram can reveal the possible existence of anisotropy in different directions of a variable over the model field. From the known data points, an experimental variogram is calculated using eq. 8:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{(i,j)|h_{ij}=h} (v_i - v_j)^2, \qquad (8)$$

where $N(h)$ denotes the number of pairs of points separated by a lag distance h. For each pair (i and j) with approximate distance h, the quadratic sum of the difference between the data values of these is calculated $\sum(v_i\text{-}v_j)^2$. The experimental variogram can then be described as the mean of the variance between the paired data values.

To facilitate interpolation, parameters of theoretical variogram models must be fitted to the experimental variogram. For the datasets in the studies of this thesis, combinations of four different variogram models were used: (1) Nugget effect, (2) Exponential, (3) Gaussian, and (4) Spherical (see e.g. Cressie, 1985).

A nugget effect model describes completely random variability within the shortest sampling intervals that depends neither on coordinates nor on the lag distance (Webster, 2008). Measurement and interpretation errors contribute to this variance. If the nugget effect is to be relevant, it must be combined with other models. The nugget effect is defined as:

$$\gamma(h) = s, . \tag{9}$$

for h>0. The exponential variogram is defined using eq. 10:

$$\gamma(h) = s\left(1 - e^{-3h/r}\right). . \qquad (10).$$

The Gaussian variogram is defined using eq. 11:

$$\gamma(h) = s\left(1 - e^{-3h^2/r^2}\right). . \qquad (11).$$

The spherical variogram is defined using eq. 12:

$$\gamma(h) = \begin{cases} s\left(\frac{3h}{2r} - \frac{h^3}{2r^3}\right) & h<1 \\ s & h\geq 1 \end{cases}. \qquad (12).$$

In the case where $h = 0$, $\gamma(h)$ also equals 0. In equations 8-12, *s* and *r* denote the sill (limit of the variogram value when h tends towards infinity or the global variance of all data points) and range (the distance when the difference between the variogram value and the sill is negligible; the correlation range is reached at this distance) respectively, see Figure 5.

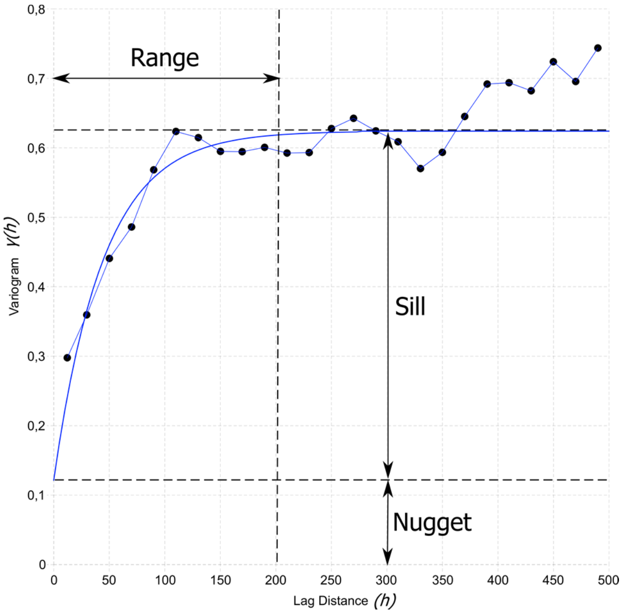

Figure 5 Experimental (black dots) and modelled variogram (blue lines) with range, sill, nugget and lag distance.

To fit a theoretical variogram model to the experimental variogram, visual fitting or the least-square (LS) method can be used (as in Paper II), see e.g. Pesquer et al. (2011). With LS, sill and range parameters for the modelled variogram are chosen to ensure it minimizes the quadratic sum of the difference between the theoretical and experimental variogram, see Cressie (1985). With ordinary kriging, the modelled variogram is used to estimate values at every point to be interpolated by eq. 13:

$$\hat{v}_0 = \sum_i w_i * v_i, \qquad (13).$$

where:
v_i is the sampled value,
w_i is a weight factor calculated from the modelled variogram and the distance between v_i and v_0.

4.4 Other methods for stratification modelling

In contrast to ordinary kriging, simple kriging assumes a known mean (Olea, 1999a), universal kriging is where a general polynomial trend model is assumed (Olea, 1999b). In the case of indicator kriging, the probability of the presence of a certain soil category in a grid cell is modelled, see e.g. Sidorova and Krasilnikov (2008) and Deutsch and Journel (1997). Other approaches, based on Markov chain analysis, have been used for modelling categorical data in geology, see e.g. Rosen and Gustafson (1996), Rosenbaum et al. (1997), Norberg et al. (2002) and Carle and Fogg (1997). Spatial simulation of material categories in comparison to an approach with continuous layers can be beneficial in very heterogeneous environments with complex layering. Nevertheless, the assumption of continuous layers modelled using ordinary kriging is expected to be sufficiently detailed for the case studies. Furthermore, it simplifies modelling and makes simulation more efficient, since data is stored in a few entries in two-dimensional tables instead of three-dimensional arrays in high resolution.

For the hydrogeological system, it is also necessary to model structures in bedrock, since dominant fractures can transport more water. In order to model fracture planes in bedrock geometry, an approach other than the one presented in Paper II is needed. Zetterlund et al. (2011) describes how the probabilistic T-PROGS method (Carle, 1999) can be used to model different structures in a rock mass. This method is based on Markov chain analysis for estimation of transition probabilities from one material to another, and indicator kriging for performing the spatial estimation of material distributions across the modelled volume. Other methods for simulation of a fracture network include e.g. FracMan (Dershowitz, 1992) and 3DEC (Itasca Consulting Group, 2012). In the groundwater models presented in Papers IV and V, the location of fracture zones is modelled based on geological interpretations in a non-probabilistic approach. Instead of applying a probabilistic approach to the location of the fracture zones, the zones have been parameterized probabilistically, see Section 5.6.

5 GROUNDWATER IN BEDROCK AND SOIL

The cause-effect chain is initiated with a disturbance of the present-state hydrogeological conditions when constructing below the groundwater table (no. 1 in Figure 1 and Figure 3). This disturbance causes leakage of groundwater into the construction, which propagates as groundwater drawdown (reduction of piezometric heads) (no. 2) and reduction of pore pressure in the cause-effect chain (no. 3). When estimating the possible extent and magnitude of groundwater drawdown, the water balance (infiltration, storage and runoff to the aquifer) and the groundwater flow pattern need to be carefully evaluated. The groundwater flow pattern is governed by drainage and infiltration conditions, layering of porous and semi-permeable soil layers, and fracture structures in the bedrock.

5.1 Groundwater flow and storage

Groundwater flow in porous and fractured media can normally be assumed to be laminar (Fetter, 2001; Gustafson, 2012) with exceptions for rocks with large openings, such as karst, see e.g. Giese et al. (2018). With this assumption, Darcy's law holds:

$$Q = K \frac{\Delta h}{\Delta l} A \quad (14)$$

Darcy's law describes the proportional relationship between flow *(Q – m^3/s)* through a porous medium versus its hydraulic conductivity *(K – m/s),* the groundwater pressure gradient *($\Delta h/\Delta l$)* and the area (A – m^2) through which groundwater is flowing.

In this thesis, the term "aquifer" is defined as a groundwater-bearing unit in soil or bedrock with greater permeability than clay deposits, regardless of its practical potential for utilizing or storing groundwater. Clay deposits are considered to be aquitards. For aquifers, it is useful to define the hydraulic transmissivity *(T – m^2/s)* which is the product of K and the saturated thickness (b – m) of the aquifer (Fetter, 2001):

$$T = bK. \qquad (15)$$

For an aquifer containing layers with different K, the total aquifer transmissivity is the sum of the transmissivity of each layers.

Porous materials have storage properties that describe their capacity to store and release groundwater. These properties affect the transient groundwater flow and drawdown process. The storage coefficient or storativity (S) is the volume of water that will be released from storage per unit of decline in the piezometric head, per unit of area in the aquifer. S is defined as:

$$S = \frac{dV_w}{\Delta h}\frac{1}{A} = S_s b + S_y, \qquad (16)$$

where:
dV_w is the volume of water released from storage (m^3)

h is the piezometric head (m)
S_s is the specific storage (1/m)
S_y is the specific yield (%)
b is the thickness of the aquifer (m)
A is the area (m^2).

Specific yield (S_y) is the drainable porosity, i.e. the ratio between the volume of water that drains by the force of gravity and the total volume of the material (less than or equal to effective porosity).

Specific storage (S_s) is the amount of water that a portion of an aquifer releases from storage while remaining fully saturated. When the head declines, the soil skeleton compresses and the effective porosity decreases. This process means that S_s correlates with the compressibility of the soil and water (Jacob, 1940, 1950; Cooper, 1966):

$$S_s = \rho_w g(\alpha + n\beta), \qquad (17)$$

where:
ρ_w is the density of water (kg/m^3)
g is the acceleration gravity (m/s^2)
α is the compressibility of the aquifer skeleton (m^2/N)
n is the porosity (%)
β is the compressibility of water (m^2/N).

For a confined aquifer which always remains saturated, eq. 16 can be simplified to: $S=S_sb$ (Fetter, 2001).

In Section 5.8, the consolidation process in the clay layer as a result of reduction of piezometric heads in the confined aquifer is calculated with Terzaghi's one-dimensional consolidation theory (Terzaghi, 1923, 1943) where the egress of water from the soil pores is governed by Darcy's law. If the compressibility of water is neglected, eq. 16 can be simplified to:

$$S_s = \rho_w g\alpha. \quad (18)$$

In geotechnical engineering, the coefficient of volume compressibility (m_v) evaluated from oedometer tested clay samples is commonly used instead of the compressibility of the aquifer skeleton (α) (Knappett & Craig, 2012). In the clay samples of the case-studies, different compression modulus M ($m_v= 1/M$) are evaluated (Persson, 2007), see Section 6. With the compression modulus in the elasto-plastic range, M_L (Section 6), a consolidation coefficient (c_v) can be calculated:

$$c_v = \frac{k*M_L}{\rho_w g}, \quad (19)$$

where:
k is the hydraulic conductivity of the clay layer (m/s),
M_L is the module M_L (kPa), see Section 6

From c_v, Terzaghi's one-dimensional consolidation equation can be solved (see Section 5.8) in accordance with the concept of specific storage since and Darcy's law.

5.2 The hydrogeological system of the cause-effect chain

To estimate the leakage and the extent of the groundwater drawdown and the pore pressure reduction, a comprehensive understanding of the hydrogeological system is necessary. This understanding needs to assess the hydrogeological conditions on a large scale since groundwater drawdown can affect large areas and the groundwater flow is dependent on the water balance within the whole catchment area. Blöschl and Sivapalan (1995) suggest a four-level scale division of catchment hydrology: (1) the small local scale with flow in macropores (soil) or individual fractures (bedrock); (2) hillslopes where the preferential flow occurs through high conductivity layers; (3) catchments with different properties between soil and bedrock types, and; (4) the regional scale with large-scale geological formations. Depending on the project phase and the consequence of the leakage, different scales are of relevance. An early-stage risk assessment should start on a larger scale and continue the analysis on a smaller scale when more information becomes available. The local scale is of interest when the tunnel inflow from individual fractures can be significant and critical. The methods presented in this thesis are, however, directed at the second-largest and third-largest scales. On hillslope and catchment scales, materials are separated, depending on their hydraulic conductivity, from the geometric model of bedrock and soil.

In crystalline bedrock, groundwater flows in secondary porosity fractures. The bedrock's primary porosity is negligible from a practical point of view (Gustafson, 2012). The hydraulic conductivity of crystalline bedrock depends on its fracturing and weathering, see e.g. Lachassagne (2008). Fractures are formed by the history of the bedrock's tectonic activity whereas weathering is dependent on the bedrock's mineralogy and history of chemical, physical and biological processes, see e.g. Pidwirny (2012). In general, hydraulic conductivity decreases with depth below the surface as weathering effects decrease at deeper levels along with a reduction in fracture apertures (width of an open fracture), whilst rock stress increases at greater depths (Gustafson, 2012). In the case studies in Papers IV and V, the bedrock is assumed to be more conductive at its more weathered uppermost part and along fracture zones, and is less conductive elsewhere.

To characterize the hydrogeological properties in soil, materials are divided according to their grain size. The hydraulic conductivity in soil materials depends on its grain size distribution, its texture, and the dynamic viscosity of water (dependent on temperature, salinity and atmospheric pressure), see e.g. Fetter (2001). From the geological model applied in Papers II-V, soil materials are distinguished between coarse-grained and fine-grained (clay). Although the hydraulic conductivity can vary by several orders of magnitude within these categories, the vast majority of the borehole classification in the case studies is not sufficiently detailed to develop a model with a more detailed stratigraphic representation.

5.3 Water balance and groundwater recharge

Groundwater recharge is related to the general water balance equation:

$$R = P - E - \Delta S, \qquad (20)$$

where R is runoff, P is precipitation, E is evapotranspiration and ΔS is the change in storage. This equation can be refined to a water budget of an urban catchment area (Fetter, 2001):

$$q = P + q_{swin} + q_{iw} + q_{gwin} - (E + E_{rv} + q_{swout} + q_{exp} + q_{gwout}) \pm \Delta S, \quad (21)$$

where:
P is precipitation
q is groundwater recharge,
q_{swin} is surface water inflow,
q_{iw} is imported water e.g. from leakage of water distribution systems,
q_{gwin} is groundwater inflow from adjacent areas,
E is evapotranspiration
E_{rv} is reservoir evaporation,
q_{sw} is surface water outflow,
q_{exp} is exported water from e.g. pumping wells,
q_{gwout} is groundwater outflow.

An urban setting can locally imply reduced natural recharge from precipitation because of sealed soil cover and stormwater drainage. Despite this reduction, recharge in urban areas is often increased significantly by leakage from drinking water and sewage water systems (Lerner, 2002). In Sweden, the leakage from drinking water distribution systems is in general about 25 per cent (Statistics Sweden, 2017). Lerner (2002) argues that the complexity of these systems and the lack of data make it difficult to accurately estimate urban recharge, which also applies in the case studies in Papers IV and V. Although precipitation rates are estimated in both case studies, the other factors that determine the groundwater recharge remain uncertain. This large degree of uncertainty is assessed using probabilistic modelling and large intervals of the prior estimates, see Section 5.6.

5.4 Hydrogeological investigations

Except for distinguishing the hydrogeological properties from the categories in the geometric model, hydrogeological investigations provide additional details of the properties within each material, see e.g. Cunningham and Schalk (2011). A hydrogeological investigation on a large scale (especially in an urban area) includes several challenges. The hydrogeological system in a city is often very heterogeneous due to the variation in anthropogenic disturbance of the water balance. These disturbances include sealed surfaces leading to increased surface runoff and reduced infiltration, groundwater flow barriers due to constructions, leakage into constructions, leakage from water distribution and sewage systems, and infiltration of water compensating for leakage into constructions. To obtain an understanding of the hydrogeological system in a city, use can be made of studies of groundwater observation time series, measurements of leakage in tunnels and pipes, and comprehensive modelling approaches that include groundwater, surface water and the hydraulic effects of constructions. In addition to these aspects, specific information can be acquired from field tests, such as the pump test, see e.g. Kruseman et al. (1990), slug test (Bouwer & Rice, 1976; Bouwer, 1989; Butler, 1997), screening curves of soil fractions (Hazen, 1911; Fair & Hatch, 1933; Andersson et al., 1984), and oedometer tests of clay samples (Swedish Standard Institute, 1991; European Committee for Standardization, 1997).

When evaluating the results of a test, it is necessary to relate the scale of the test method to the scale of the problem to be assessed. This assessment can include other sources of information, such as the interpreted geology in the area, other test results, and modelling results. When evaluating K from oedometer-tested piston samples, a very small volume of the total clay volume is tested. If the clay is not homogenous but layered with more coarse-grained material, the evaluated results could differ significantly from what is representative of the total volume. Similarly, a slug test is only representative of the volume in the immediate vicinity of the filter of the tested well and can deviate significantly from the total volume of the material of interest. Furthermore, with pumping tests that are assumed to produce more reliable results valid for larger areas, the results need to be critically assessed. In urban locations, test environments can be uncontrolled because of unknown factors: leakage rates from pipes, facility location and rates of infiltration, and leakage rates into sub-surface constructions. This setting, together with a heterogeneous environment, can results in tests that are problematic to evaluate along with a multiplicity of contradictious results at short distances from each other.

5.5 Hydrogeological safety measures

The most common technique to reduce the inflow into a bedrock construction is to seal the water-bearing fractures by grouting or lining with concrete elements (associated with step 1 in the cause-effect chain, Figure 3). With grouting, boreholes are first drilled into the rock mass, after which grout is injected under pressure to fill the fractures (Butrón et al., 2010; Grøv et al., 2014; Stille, 2015). If sealing the inflow with the aid of grouting is not sufficient, a common strategy in Swedish infrastructure projects is to compensate for leakage and to maintain groundwater levels by means of artificial infiltration of water in injection wells (associated with step 2 in the cause-effect chain, Figure 3). Since water is injected into the well, a cone of higher groundwater heads close to the well will be formed. When designing the injection well, it is important that the soil or bedrock material has sufficient conductivity and storage. The construction and operation of this measure can be very expensive if large amounts of drinking water are used (see cost estimations in Paper V). Infiltration can also cause damage if e.g. basements become flooded or if the infiltrated water increases the oxygen content and causes decomposition in foundations made of wood (Björdal, 2016). Similarly, as with estimations of the extent of drawdown, detailed information on the functioning of an injection well can only be given first during its operation phase. It is therefore important to plan and bring wells into operation in good time before damage occurs.

5.6 Groundwater modelling

The groundwater models in Papers IV and V follow general principles suggested by e.g. Reilly (2001), Freeze et al. (1990) and LeGrand and Rosén (2000). In a first step, the goal of the model is defined from the scope definition in the risk assessment. In the next step, data is collected in the form of geological information, hydrogeological and geotechnical investigations, and climate and other information related to water balance conditions. From these steps, a conceptual model is defined. This model should describe the water balance conditions in terms of groundwater flow into (recharge), within (discharge), and out of the model (outflow). The inflow and outflow define the boundary conditions, e.g. outflow into a sea (Paper IV) and recharge from an adjacent esker (Paper V). Features functioning as groundwater sources and sinks can be known in terms of location and function (e.g. known pumping rates at a specific location), known in terms of location but unknown function (e.g. road tunnels and rivers without estimations of leakage), and completely unknown (e.g. secret facilities and leaking water distribution and sewage pipes).

From the definition of the conceptual model, the model is parameterized in terms of e.g. recharge and hydraulic conductivity for different materials, including variability within these materials. The parameterization should be based on general knowledge of each material together with site-specific investigations. Although there is a large variety of investigation methods for hydrogeological properties, these tests can be expensive and time-consuming (especially pumping tests) or only representative for very small volumes (slug tests, screening curves and oedometer tests). This means that an assessment of the representativeness of these properties is needed when estimating what are often heterogeneous soil and bedrock conditions. If the reliability of investigations varies between materials and locations, the assigned variability should account for this.

A calibration goal defines the required coherence between the model and available observations (e.g. groundwater heads and expected water balance). The calibration goal should be set in accordance with the expected misfit, given the model conceptualization and the measurement noise of the calibration data as recommended by Tonkin and Doherty (2009). For steady-state models, it is important to consider the variability of available observations since these are often measured during limited times in different projects without any overall coordination. In addition, observations can be affected by very local drainage conditions that are not of interest in the light of the larger scale of the model.

In the case studies in Papers IV and V, the numerical models are constructed in the finite-difference modelling code MODFLOW (Harbaugh, 2005). Darcy's law forms the basis of the diffusion equation for transient flow on which MODFLOW is based. For three dimensions, this equation can be written as:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W = S_s\frac{\partial h}{\partial t},. \qquad (22)$$

where K_{xx}, K_{yy} and K_{zz}, are the hydraulic conductivity values along the x, y and z coordinate axes, h is the piezometric head, W is the volumetric flux per unit volume representing sources and/or sinks of water (see water balance equations in Section 5.3), S_s is the specific storage of the porous material, and t is time.

5.7 Probabilistic groundwater modelling

If the hydrogeological conditions are uncertain and heterogeneous in terms of properties, recharge and drainage conditions (as in the case studies in Papers IV and V), it would be preferable to use probabilistic groundwater modelling techniques. The numerical groundwater models in both case studies combines MODFLOW with the NWT solver (Niswonger et al., 2011) and the PEST (Parameter ESTimation code) sub-space Monte Carlo (SSMC) (Tonkin & Doherty, 2009) technique for simulation of plausible groundwater drawdown scenarios of different design alternatives. The theoretical considerations of the tools included in the PEST software suite (www.pesthomepage.org) are documented over a wide range of literature (Doherty, 2003; Moore & Doherty, 2005; Tonkin & Doherty, 2005; Fienen et al., 2009; Tonkin & Doherty, 2009; Doherty & Hunt, 2010; Doherty, 2011; Fienen et al., 2013; Rossi et al., 2014; Burrows & Doherty, 2015; Woodward et al., 2016). A detailed guideline for applying PEST to groundwater modelling uncertainty is provided by Doherty et al. (2010). The necessity for PEST SSMC arises from the typical situation of undetermined ill-posed hydrogeological problems, where many plausible model combinations fulfil a calibration criterion equally well, resulting in many non-unique solutions.

From the conceptual model and the previous soil and bedrock stratification model (Section 4), the numerical model is discretized with different layers and materials in a three-dimensional grid, Figure 6. Since thin continuous layers are also modelled where these cannot be assumed to exist (e.g. thin clay layers at high altitudes), thin layers are removed in the case studies. From the probabilistic stratification model, only the most likely material configuration is used. The hydraulic transmissivity (eq.

15), determines the flow in an individual layer. T can be adjusted either from the material thickness (*b*) or from *K*. With the choice of only including the most likely material configuration, solely adjusting *K* instead of a combination of both *K* and *b* simulates possible model deviations of *T*.

Fields of material properties to assess heterogeneity and anisotropy are modelled using pilot points (Doherty, 2003) in the different materials. Pilot points (*PP*) is a 2D scatter point set representing different locations within a material. The parameter variability in each of these sets is defined from the previous parameterization stage, with the possibility of assigning fixed values to locations where the parameter value is reliable. As recommended in Doherty (2003), *PP* should be placed with high spatial density throughout the model domain to capture heterogeneity and avoid numerical instability. From the *PP*, a spatially distributed parameter field is modelled using kriging and a variogram that approximates the heterogeneity of the parameter (see Section 4).

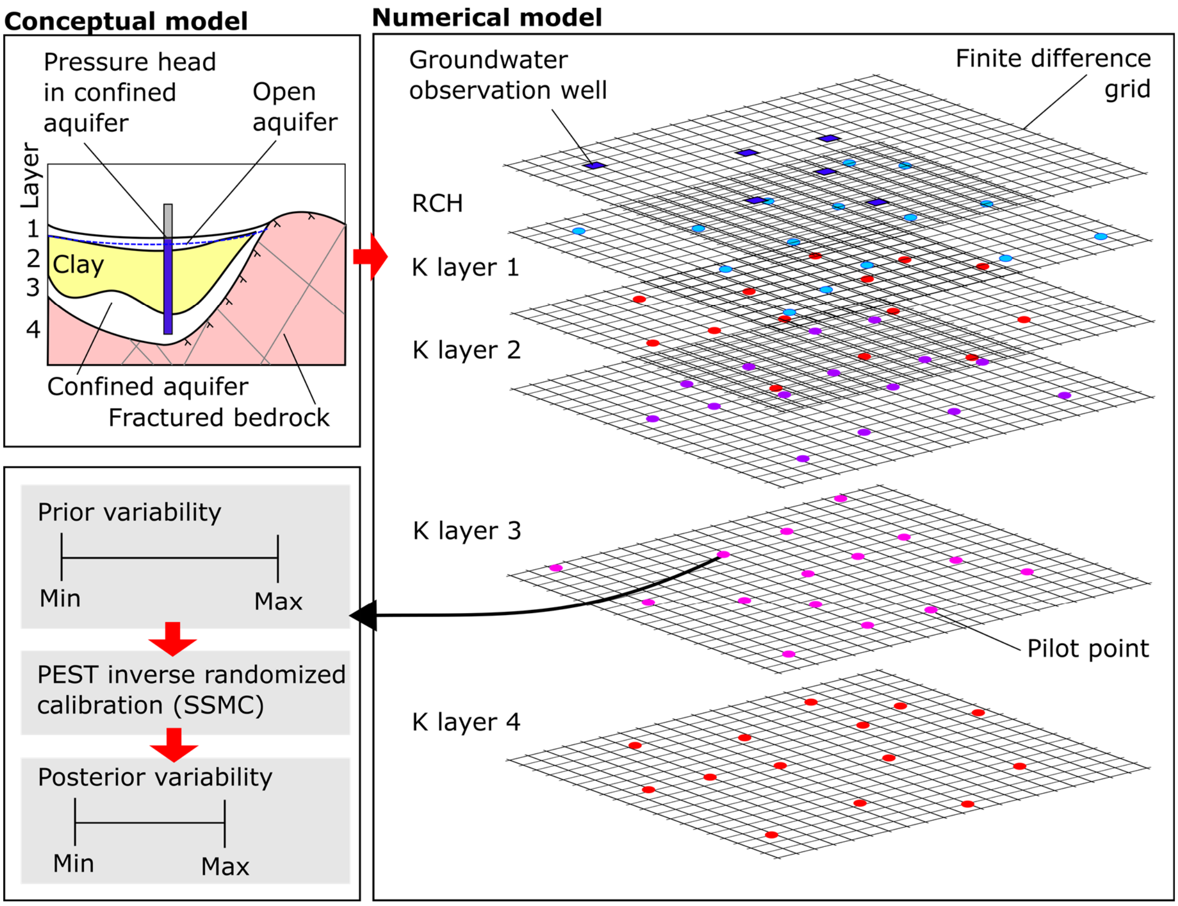

Figure 6 Procedure for model conceptualization, definition of a numerical model with grid layers and randomized inverse calibration with PEST (modified from Paper V).

In a first numerical modelling step, the model is calibrated by manually adjusting the parameter sets to achieve good coherence with observations (groundwater heads and water balance). This calibration is then improved with a PEST calibration to achieve a solution with minimum error variance.

The goal of an inverse calibration with PEST SSMC is to find a sufficiently large number of parameter combinations that meet the calibration criterion (calibration-constrained Monte Carlo simulation). Each parameter combination that meets the calibration criterion results in a model solution. To improve model efficiency in terms of computing time, PEST uses mathematical regularization through singular value decomposition (SVD). This process is initiated using a base parameterization with a large number of native model parameters, since each PP represents a parameter. Secondly, sensitivities of the base parameterization are calculated. A matrix that decomposes the base parameters is constructed from these sensitivities. As described in Tonkin and Doherty (2005), SVD is used to introduce factors of principal eigenvectors (super-parameters) to this matrix. Since the number of super-parameters may be far less than the base parameters, the computational burden is greatly reduced. The super-parameters belong to the calibration solution space. In addition, there are also base parameter combinations that have no effect on the simulation of available observations. These insensitive combinations are referred to as the null space, where any parameters within it can be added without affecting any solution to the inverse problem (Doherty et al., 2010). The MC process is initiated by a stochastic generation of parameter fields (values of PP) from the modeller's prior estimates (prior variability in Figure 6). The difference between the prior calibration and the randomization is then projected onto the null space. If the randomization results in a model that is no longer calibrated, parameter combinations in the solution space are re-estimated and the null space-projected parameters are retained as additive values (Tonkin & Doherty, 2009). This process results in post-calibrated parameters and the difference between these provides an estimate of parameter uncertainties of the model (less posterior than prior variability in Figure 6). These uncertainties are conditioned on the original model calibration results together with the model structure and boundary conditions.

Although the process is conditioned on the calibration criterion, it is possible that some randomizations do not meet this criterion or result in an unreasonable water balance. In these cases, it is important that the modeller reviews these solutions based on expert knowledge, see e.g. the discussion on "hydrosense" in Hunt and Zheng (2012). In the case studies, this revision considers two specific criteria related to the difference between simulated and measured heads and deviations in water balance between inflow and outflow. After this revision, *n* calibrated randomized parameter solutions remain, with different parameter settings and water balance conditions (see left-hand part of Figure 7). All these *n* solutions meet the calibration criteria equally well but since the parameterization differs, the response of changed water balance conditions in these models is also expected to differ.

From the *n* calibrated randomized solutions, the effect of changed drainage conditions from different design alternatives (defined in the decision problem prior to the risk assessment) are modelled in each solution (see right-hand part of Figure

7). The design alternatives (A_i, with index $i=1\ldots m$, A_0 is the reference alternative and m is the number of alternatives) include sub-surface construction and safety measures to reduce the effect of the leakage. When modelling these m alternatives in the n calibrated randomized solutions, these simulations result in a range of effects on the water balance and groundwater heads. For each alternative, the range of, for example, the change in groundwater head or inflow into the construction, can be compared with a tolerability criterion (in Paper V the groundwater drawdown should not be greater than 0.5 or 1 m within a risk area) defined for these parts in the cause-effect chain as discussed in Section 3. The result can also be integrated with the subsequent parts in the cause-effect chain for a comprehensive risk assessment (as in Paper V).

When new information is available, the whole modelling process can be repeated, including the conceptual model and changes in the design alternatives. The groundwater models in Papers IV and V were reconstructed several times because of convergence problems, deviations between observation data, and unreasonable water balances. The design alternatives were also changed several times since some alternatives resulted in unreasonable inflow rates from injection wells (Paper V) or heads that are too high as the sealed construction functioned as a barrier instead of a drain (Paper IV).

In addition to the above-described PEST method, there are other probabilistic methods, using stochastic simulations, to address parameter uncertainties (Dagan, 1982; Carle & Fogg, 1997; Strebelle, 2002; Neuman, 2003; Mariethoz et al., 2010), or inverse modelling, see Carrera et al. (2005). Except for parameter uncertainties in the input data, uncertainties in hydrogeological models originate from conceptual uncertainties and the equation-solving algorithm (Konikow & Bredehoeft, 1992). If a probabilistic modelling approach alone is used to account for uncertainties, Konikow and Ewing (1999) state that only some uncertainties are accounted for since PDFs can be incorrect and conceptual and numerical models other than the one used are not included. If only a restricted agenda of defined and tractable uncertainties is considered, an invisible range of other uncertainties, especially about the applicability of the existing framework of knowledge to new situations, are ignored (Wynne, 1992). This ignorance limits the capability of a model to predict future scenarios. Hunt and Welter (2010) argue that there will always be "unknown unknowns" of structural errors regardless of parameterization efforts. This means that if a system is characterized by uncertainties and only the ones that are easy to assess are considered in a model, the model might reduce some uncertainties but will increase ignorance since the unknown unknowns are not considered.

Conceptual uncertainties can be addressed by a discussion of contrasting professional judgements and an evaluation of different scenarios (Seifert et al., 2008; Gillespie et al., 2012; Hunt & Zheng, 2012) or using structured methods for self-evaluation (Van der Sluijs et al., 2005). Different assumptions and conceptualizations of the system can be equally reasonable but produce substantially different results when applied in a model. An example from a case study in Copenhagen showed that five different consultants reached substantially different conclusions on the vulnerability of a water supply, although all were given the same information (Refsgaard et al., 2005). The conceptual model can also be updated and re-evaluated based on the outcome of the numerical model and new information as discussed in e.g. LeGrand and Rosén (2000); Gillespie et al. (2012); and Bredehoeft (2003, 2005). Comparing simple calculations with results from a more advanced code (Haitjema, 2015), or comparing different and more advanced models with each other (Holländer et al., 2014) are strategies that can be employed to evaluate the reasonableness of the equation-solving algorithm. A review of the strategies to handle uncertainty in groundwater flow modelling is presented in Refsgaard et al. (2012).

5.8 Reduction in pore pressure

The lowering of groundwater heads above and/or below a clay layer creates an excess pore pressure gradient (Δu), which causes discharge of water from the clay layer. This consolidation process is related directly to the degree of subsidence, see e.g. Fang (2013). Changes in pore pressure are calculated in Paper III from a probabilistic soil-stratification model, interpolation of groundwater heads, and assumed uniform drawdown magnitudes across the model area. In Paper IV, changes in pore pressure are calculated from a probabilistic soil stratification model and a probabilistic groundwater model with different design alternatives. Although it would be possible to model changes in pore pressure in the clay layer with a more direct coupling to the MODFLOW model, e.g. with the SUB (Hoffmann et al., 2003) or SUB-WT (Leake & Galloway, 2007) packages, these models are not implemented using a probabilistic stratification model. Another reason for the choice of not modelling the consolidation process in MODFLOW is that a transient model that represents the process at different depths requires a large number of grid cells in the clay layer, which would slow down the PEST NSMC process or make it unfeasible in the light of the computing capacity available for this project.

In Paper IV, pore pressure is calculated from the calibrated groundwater model solutions (before groundwater drawdown - simulation 1-n in the left-hand part of Figure 7) and the corresponding simulation with a design alternative (after groundwater drawdown – right-hand part of Figure 7). After a soil stratification profile has been simulated, groundwater heads in layers 1 and 3 (above and below the clay layer) are simulated from the accepted groundwater model calibrations with a uniform distribution, $U(1,n)$. From these, the pore pressure (u) is calculated as a straight line between the pressure heads at the bottom and top of the clay layer before (Figure 7A) and after (Figure 7B) groundwater drawdown. This calculation assumes a linear dependency between the coarse-grained layers above and below the clay layer, see e.g. Persson (2007) and Zeitoun and Wakshal (2013). If layer 1 is dry and the pressure head in layer 3 is below the upper edge of the clay, u is calculated hydrostatically using the head in layer 3. Note that in the example in Figure 7 there is no change in head in the uppermost layer, only in layer 3. In Paper III, the calculation is similar, but only the soil stratification profile is simulated probabilistically since groundwater heads are represented by interpolation from point information (without representation of variability).

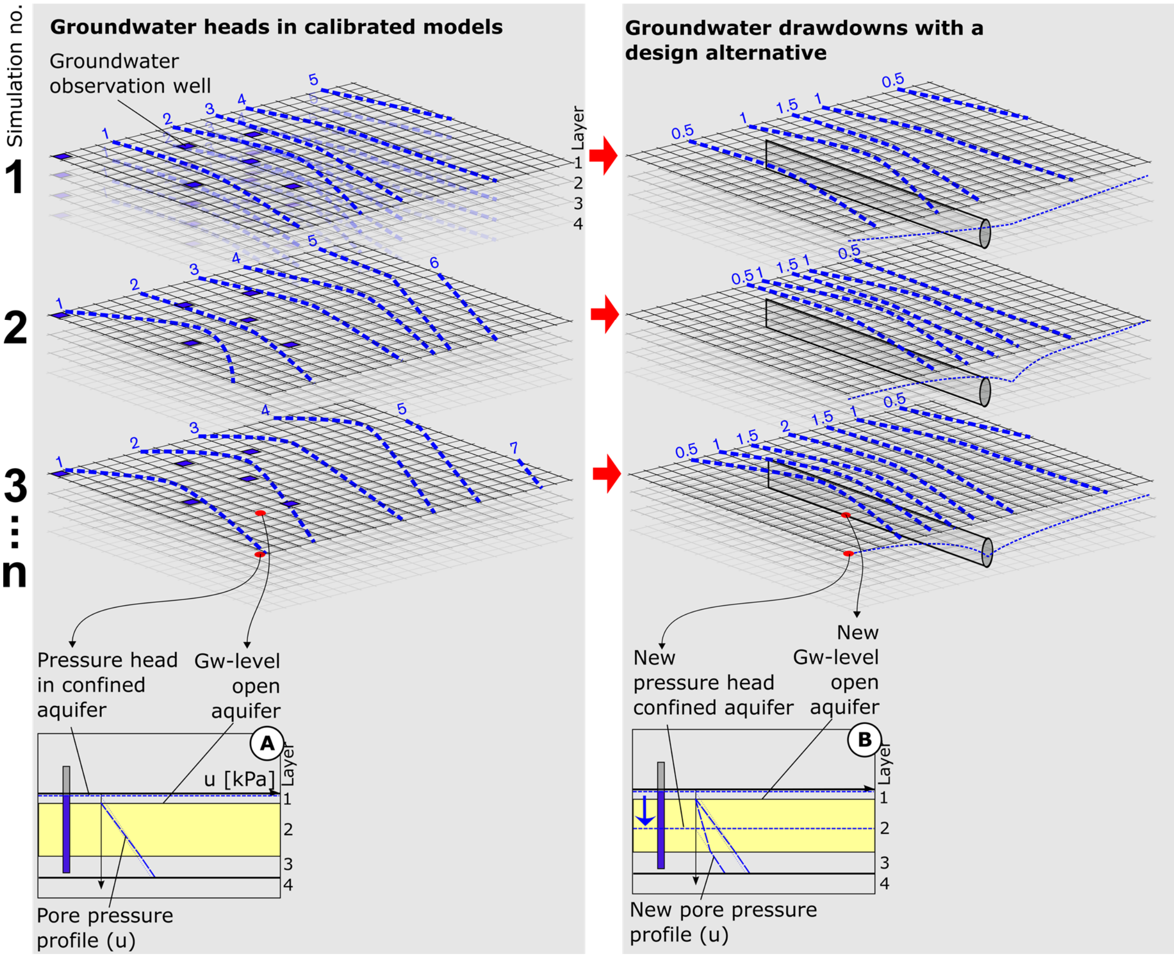

Figure 7 Calculation of pore pressure and effective stress from calibrated groundwater models and models with drawdowns. Modified from Paper IV.

The above calculation of *u* considers the steady-state conditions at the end of the consolidation process. Since the groundwater model in Paper IV is steady state and does not take into account the transient flow process, it is conservatively assumed that the drawdown in the coarse-grained material in layers 1 and 3 occurs immediately.

The change in pore pressure conditions gives rise to a hydraulic gradient, in response to which the pore water leaks out of the soil (and the soil deforms). This is a time-dependent consolidation process where the pore water pressure gradually returns to equilibrium. The consolidation process in the clay in layer 2 is calculated in Publication IV using Terzaghi's one-dimensional consolidation theory (Terzaghi, 1923, 1943). The approximate solution applied in Paper IV is based on Fourier decomposition of the propagation of pore pressure as described by Taylor (1948). Finite-difference approaches for more precise calculations would also be possible, see e.g. Knappett and Craig (2012). With the present solution, the clay layer is first divided into 0.1 m increments. In each of these increments, a consolidation coefficient (c_v) and a time factor (T_v) produce a consolidation ratio *(U_z)*:

$$T_v = c_v \frac{t}{H^2}, \quad (23)$$

where:
c_v – consolidation coefficient (eq. 19),
t – time after consolidation is initiated (sec.),
H – length of drainage path (metres), assumed to be half the clay thickness since modified groundwater conditions can occur in both the layer above and below the clay,

$$U_z = 1 - \sum_{m=0}^{m=\infty} \frac{2}{M} \left(\sin \frac{M_t z}{H}\right) e^{-M^2 T_v}, \quad (24)$$

where:

$$m = \frac{n-1}{2}, \quad (25)$$

and n is an integer with an initial value of 1 up to a sufficiently high value to assure linearity with Terzaghi's solution, and:

$$M_t = \frac{1}{2}\pi(2m+1), \quad (26)$$

where z – is the depth below the upper limit of the clay layer (m). Note that M_t is not a compression modulus in this equation but a parameter in eq. 24.

The calculation is shown in Figure 8, where the change in pore pressure after final consolidation, $\Delta u(t_{max})$, is multiplied by U_z to calculate the pore pressure change, $\Delta u(t)$, and the pore pressure, $u(t)$, after a certain time, t. The resulting pore pressure calculation, $\Delta u(t_{max})$ and $\Delta u(t)$ can then be combined with a subsidence model.

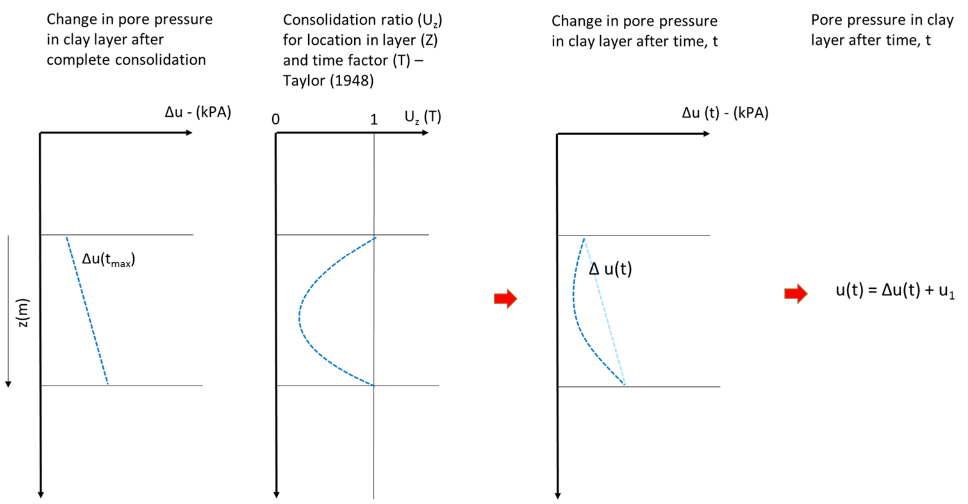

Figure 8 Calculation of the change in pore pressure, $\Delta u(t)$, after a certain time using consolidation ratios (U_z). u_1 represents the new pore pressure profile after final consolidation from groundwater drawdown in Figure 7.

6 SUBSIDENCE IN SOFT SOIL

Consolidation settlement in soft soils occurs because of dissipation of pore pressure when the effective stress changes. Alongside this process, secondary consolidation or creep deformations can occur as a result of plastic adjustments of the soil particles. The theory of deformation of porous medium soils containing water in the voids is based on the principle of effective stress *(σ'),* introduced by Terzaghi (1923). This principle states that the total stress, *(σ)*, consists of the sum of σ' (inter-granular stress carried by the soil skeleton) and the pore pressure *(u),* or expressed in other terms: $\sigma' = \sigma - u$. With a reduction in pore pressure in clay, the stress increases *($+\sigma'$)*. This causes vertical compression *($-\varepsilon_v$)* but also a (small) lateral change *($\Delta\varepsilon_h$)*. Since materials expand and compress in different directions depending on the direction of the force, the stress-strain relationship is three-dimensional. Often, stress-strain is simplified to a one-dimensional relationship with the same direction as the force (no lateral strains), see e.g. Fang (2013). This simplification is applied in the methods in Paper III and IV.

The deformation process is dependent on the stress history of the clay, e.g. groundwater level changes and previous (eroded) surcharge. If the current effective stress (σ'_v) is equal to or smaller than the greatest past effective stress (σ'_c), the clay is normally consolidated (NC) or over-consolidated (OC) respectively. The quotient between σ'_c and σ'_v describes the over-consolidation ratio (OCR). In Papers III and IV, the one-dimensional model by Larsson and Sällfors (1986) is used to calculate subsidence for the two consolidation states. This method is well established in Sweden and was chosen due to the fact that the laboratory tests from the infrastructure projects that constitute the case studies were appropriate for this method. The Swedish model is internationally less recognized than the compression index method, see e.g. Fang (2013). Nevertheless, the principle of probabilistic modelling from PDFs of compression parameters demonstrated in Papers III and IV would also be applicable to the compression index method. Comparisons and transformations between the different methods, can be found in e.g. (Larsson, 1986; Olsson, 2010; Fellenius, 2017).

The Swedish method is similar to Janbu's tangent modulus approach (Janbu, 1967) where the soil compressibility of the two states is evaluated from a diagram where vertical strain (ε) is plotted against effective vertical stress (σ'_v) and a different modulus of compressibility ($M=d\sigma'_v/d\varepsilon$) is evaluated, see Figure 9. In the Swedish method, the evaluation is based on a constant rate of strain (CRS) on oedometer-tested clay samples. Benefits of CRS include generation of a continuous stress-strain curve and a shorter test period. Disadvantages include inability to evaluate creep (secondary or delayed consolidation with no change in the stress state) (Larsson & Sällfors, 1986) and dependence between the measured response and the applied strain rate (Sällfors, 1975; Claesson, 2003; Pu & Fox, 2016).

From the CRS test, three stiffness regimes with different modulus of compressibility *(M)* as a function of σ'_v can typically be evaluated from testing of clay samples using the Swedish method (Figure 9).

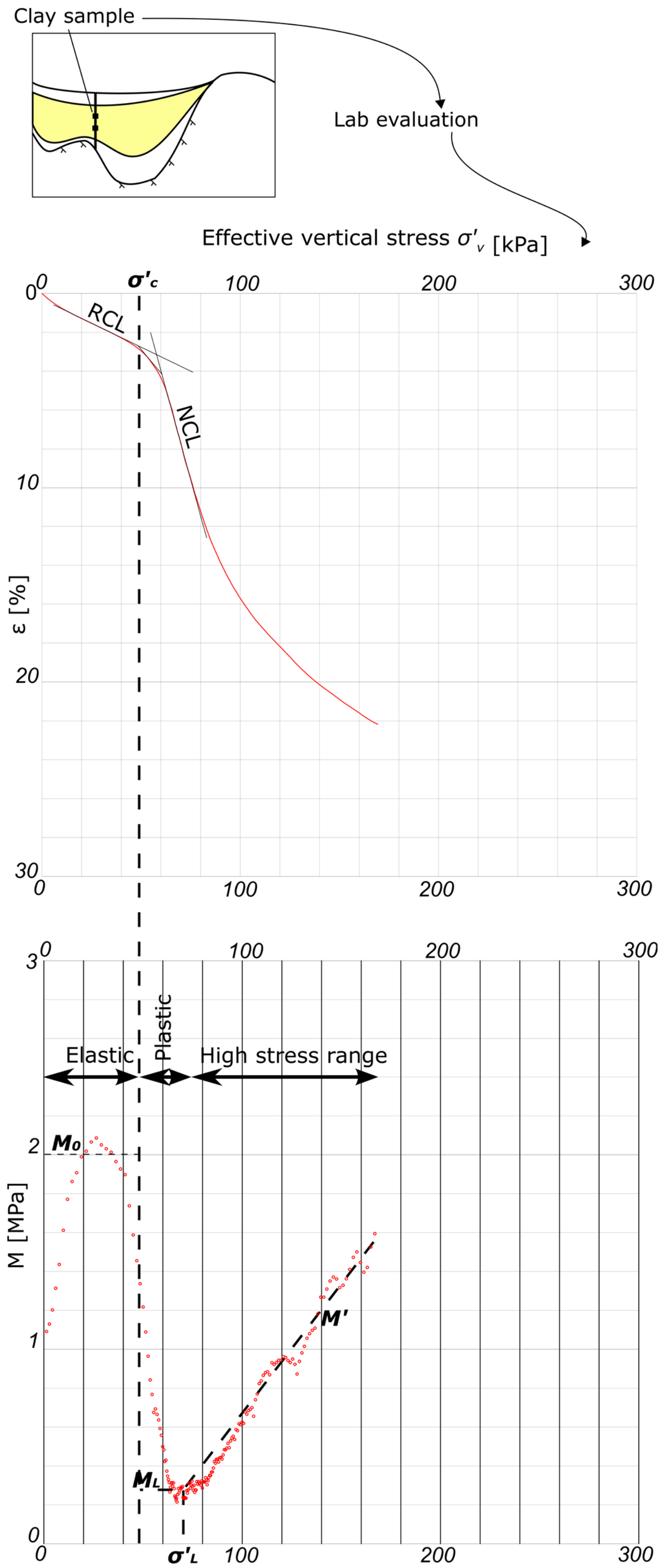

Figure 9 Example of results from a CRS test and evaluated parameters σ'_c, σ'_L, M_L, M_0 and M' from a clay sample in Stockholm together with the three stiffness regimes (modified from Paper III).

The initial stage in the consolidation process in the Swedish method is considered to be linear elastic ("elastic" in Figure 9). An essential feature of the elastic phase is that the strains are reversible when the material is loaded and unloaded. In addition, there is a one-to-one relationship between stresses and strain in the elastic phase. At this range, σ'_v is less than σ'_c and the strain-stress plot of this over-consolidated part follows a recompression or swelling line (RCL). As discussed in e.g. Olsson (2010); Fang (2013), the methods for estimating the modulus M_0 in this stage produce results with significant uncertainties. In Paper III, the modulus M_0 is evaluated with the empirical relationship based on undrained shear strength from fall cone tests, τ_{fu}, $M_0 \approx 250*\tau_{fu}$ as suggested by Larsson et al. (1997) and Moritz (1995). In Paper IV, the evaluated M_0 from CRS-test is multiplied by 3 as recommended by Sällfors (2001). Despite these simplifications, subsidence magnitudes in the RCL part are in general small.

In the second stage ("plastic" in Figure 9), plastic conditions are reached at stresses larger than σ'_c. At these stresses, strain increases and plastic hardening occurs until a new yield condition is created, see e.g. Olsson (2010) and Olsson (2013). Due to this hardening, the transition phase between elastic and plastic conditions is moved along the direction of the applied stress (for one-dimensional problems). Except for irreversible deformations, this process increases σ'_c. This means that if the soil is unloaded and reloaded with a stress between the old and the new increased σ'_c, the deformation will be in the initial elastic phase. In the second stage, the stress-strain relationship follows a normal compression line (NCL). The intersection between RCL and NCL estimates σ'_c. In Sweden, the industry standard for estimating σ'_c follows a graphical method introduced by Sällfors (1975), see broken line in Figure 9. Other methods for estimating σ'_c in one-dimension are described in e.g. Casagrande (1936) or Burmister (1952). At σ'_c, the modulus is assumed to drop constantly to the *second constant modulus,* M_L. The stiffness along the NCL is significantly less than along the RCL ($M_L<M_0$), which leads to larger subsidence magnitudes for stress rates in the NCL range.

At higher stresses the assumption and simplification of a constant modulus is no longer valid, and a third phase occurs (stress > σ'_L, "high stress range" in Figure 9) with a constantly increasing modulus. At this part of the curve, the modulus number M' is evaluated as $\Delta M/\Delta\sigma'$ (Larsson & Sällfors, 1986). Figure 9 presents how the compression parameters σ'_c, σ'_L, M_L, M_0 and M' correspond to the calculated curve for a sample at a certain depth below surface. Depending on the state of $\Delta u(t)+\sigma'_{v0}$ (where "0" indicates conditions before groundwater change) relative σ'_c and σ'_L, different equations for subsidence calculation are used (presented in Papers III and IV).

In the calculations in Papers IV and V, load from buildings (including any basements) and considerations of different foundation types are omitted in the calculations. The effective stress can be expected to be greater at building locations, which means that the result underestimates the calculated subsidence. On the other hand, if a building is founded on piles, the calculation may overestimate the subsidence magnitude. In addition, no samples are from soil below buildings, which could mean that the load history and compression parameters differ from the present samples at these locations. If estimations of building load are made, e.g. from the foundation type, basement level and building materials, it is feasible to incorporate this in the calculations. Another constraint on the subsidence calculation method is that secondary consolidation or creep is not considered. Creep is referred to as deformation under constant applied stress after complete dissipation of excess pore pressure as a result of plastic adjustments of the soil particles (Knappett & Craig, 2012). At stress states around and above σ'_c, creep rates are larger than in the OC range and contribute to a significant part of the total settlement (Bjerrum, 1967). Although these constraints are present in subsidence calculations in Paper III, the risk area is defined for lower subsidence magnitudes (2 cm), mainly occurring in the OC range, which is more insensitive to ignoring creep in the calculations. In Paper IV, the method is recommended to be improved with a calculation that also considers creep since the higher subsidence magnitudes at stress states above σ'_c are significant for the risk calculation in the case study. If more refined models, such as finite-difference or finite-element models, were to be used, it is likely that probabilistic calculations of subsidence would be highly demanding computationally. Even in their present state, the probabilistic models in the case studies in Papers III and IV take several days (about 2 and 14 days respectively) to compute on a current generation workstation. Despite these constraints, the order of magnitude of the subsidence calculations are expected to be reasonable for an initial risk assessment.

In addition to model structure uncertainty due to a simplified description of the subsidence process, uncertainties in the parameters driving the model are present. These uncertainties originate from three primary sources: (1) inherent variability of the soil; (2) measurement errors; and, (3) transformation uncertainty in design parameters (Kok-Kwang & Kulhawy, 1999). The scattered data describes the first two sources, which are addressed in Papers III and IV with different statistical analysis using data transformation, regression, T-tests and ANOVA. Transformation uncertainty exists in e.g. the interpretation of the point for σ'_c (Olsson, 2013). Parameter evaluations are also dependent on temperature and strain rate effects, see e.g. Sällfors and Tidfors (1989) and Claesson (2003). Despite the constraints mentioned, the order of magnitude of the subsidence calculations is expected to be reasonable for an initial risk assessment. In Papers III and IV, refined models that take into account creep, load and building foundations are recommended for highlighted buildings at risk of subsidence and damage.

7 SUBSIDENCE DAMAGE AND COST

7.1 Subsidence damage

The extent of damage caused by subsidence depends on the magnitude of the subsidence and the resilience of the risk object. This response is determined by the construction (including foundation), historical damage and the differentiation of subsidence over the building area of the object. Examples of differentiation in building response include the following: superficially founded buildings are more vulnerable than reinforced concrete structures founded at greater depths below the surface (Cooper, 2008); buildings in brick are more vulnerable than reinforced concrete constructions; long buildings are more likely to be damaged than short buildings (Karlsrud, 2015). As stated in the limitations in Section 1.4, a rather simplified approach is applied to the building response where no distinctions between the construction and foundation of buildings have been made. This simplification is further discussed in Papers IV and V.

Subsidence damage typically involve cracks as a result of different deformation modes: sagging, hogging and local (deformation in part of a building), see e.g. Bonshor and Bonshor (1996). In sagging, there are greater deformations at the centre of a building than on the sides. This causes wide cracks at the bottom and narrow cracks at the top of a building. Hogging causes large deformations on the sides of a building and small deformations at the centre, which leads to wide cracks at the top and narrow cracks at the bottom. Local deformations are typically the result of nearby subsurface construction work on one side of a building with damage similar to the result of hogging. These deformation modes can occur separately or jointly. The severity of the cracks determines the extent of the damage. Narrow cracks with aesthetic damage that can be patched relatively easily are less severe than cracks that affect the function or even the stability of a building.

To determine the consequences, it is necessary to correlate subsidence movements with the extent of the resulting damage. Subsidence movements can be measured in different ways, including absolute (vertical displacement), differential or relative (difference between two points on a building), tilt or rigid body rotation from the vertical axis of the building, angular distortion (the rotation of the line joining two reference points relative to the tilt), and horizontal strain (Wroth & Burland, 1974; Boscardin & Cording, 1989; Korff, 2013). Literature reviews of observed damage relative to subsidence movements are compiled in e.g. Boone (1996) and Son and Cording (2005). The subsidence calculation method presented in Section 6 only takes vertical movements into account. Substantial vertical subsidence does not necessarily mean extensive damage if the movement is evenly distributed over the building area. Nevertheless, substantial vertical subsidence is often correlated with movements that cause damage, as reported in different schemes, see e.g. (e.g. Skempton & Macdonald, 1956; Bjerrum, 1963; Rankin, 1988; Son & Cording, 2005; Cooper, 2008).

7.2 Estimation of damage costs

Damage costs can be divided into direct and indirect costs. Direct costs involve restoration costs due to damage, where minor superficial damage can be repaired at a relatively low cost while structural damage often entails significant costs. Since the estimation of direct costs is based on historical records, damage and expected benefits of safety measures are estimated *ex-post*. An *ex-post* estimation refers to known quantities as if the specific effect of interest (such as damage due to subsidence) has already occurred. Indirect costs associated with subsidence damage include e.g. project delays, a lower market value for the damaged building, and inconvenience for the occupiers. Such indirect costs, through which stakeholders' preferences regarding risk mitigation can be reflected, are more difficult to quantify. The costs associated with peoples' preferences must be estimated *ex ante*, using e.g. studies of willingness to pay in order to avoid disruptions associated with subsidence damage. For further details of different estimation approaches, see e.g. Boardman et al. (2011).

Although subsidence resulting from groundwater drawdown has caused severe damage in many locations worldwide (Olofsson, 1994; Karlsrud, 1999; Ortega-Guerrero et al., 1999; Burbey, 2002; Xue et al., 2005; Phien-wej et al., 2006), quantitative estimates of damage costs are sparse. In Oslo, the cost of stabilizing buildings that are at risk of subsidence is set at nearly □6 billion (Venvik et al., 2018). Cooper (2008) estimates the subsidence damage cost in the UK to be £500 million per year (not only subsidence related to groundwater drawdown). Lindskoug and Nilsson (1974) approximate the damage cost from subsidence as a result of groundwater drawdown and other loads on an area of single-family dwellings in Stockholm at about 50% of the value of the buildings.

The estimation of damage costs in Paper IV is based on a few legal cases in Sweden where *ex-post* estimations of compensation measures are applied. In Paper V, failure costs for exceeding a tolerability criterion of acceptable groundwater drawdowns (gw_{accept}) are estimated both as indirect delay costs and as direct costs for damage. A CBA is applied in Papers IV and V with the difference that a combined approach between CBA and cost-effectiveness relative to the tolerability criterion is applied in Paper V as discussed in Section 3. The different approaches are described in Figure 10a, where the economic risk (R) is expressed as a continuous function provided by a combination of the economic cost, C_s, and the probability of a damage of a certain degree, f_s (see Paper IV). Figure 10a shows the general form of exponential decay of the likelihood of damage together with damage severity, from aesthetic damage to severe functional damage and damage leading to collapse. In Paper IV, the continuous function of Figure 10a is simplified into a stepwise function reflecting three different damage categories, see Figure 10b. When subsidence is simulated, C_s is calculated for each building and simulation, resulting in a frequency distribution. The combined result from all buildings over the affected area estimates the risk for each design alternative (R_0, R_1 and R_2 in Figure 10d). Since the stepwise function is based on building area and different buildings have different areas, the exemplified curves for R in Figure 10d have more of a continuous shape, similar to the original form in Figure 10a. The areas of R for the different alternatives are different since simulations of C_s equal to zero are omitted from the graph (but are used in the risk calculation).

In Paper V, the failure cost is only related to the binary tolerability criterion of gw_{accept}, which means that no differentiation is made between different subsidence magnitudes. In this case, R_0, R_1 and R_2 are calculated from the frequency of exceeding the binary tolerability criterion together with the C_s for doing this. Instead of a continuous graph, this calculation results in a column shape of R for each design alternative, see Figure 10c. A binary tolerability criterion could be an appropriate method in areas where high values are at stake, i.e. when the consequences are severe or even catastrophic, as in the case study of central Stockholm in Paper V. A measurable criterion, such as groundwater levels also have the benefit of being easy to control and communicate to stakeholders. Nevertheless, a strict CBA could provide new insights into whether excessive safety measures are justified relative to the economic risk. From this insight, different tolerability criteria could then be defined for different areas and buildings depending on the calculated risk.

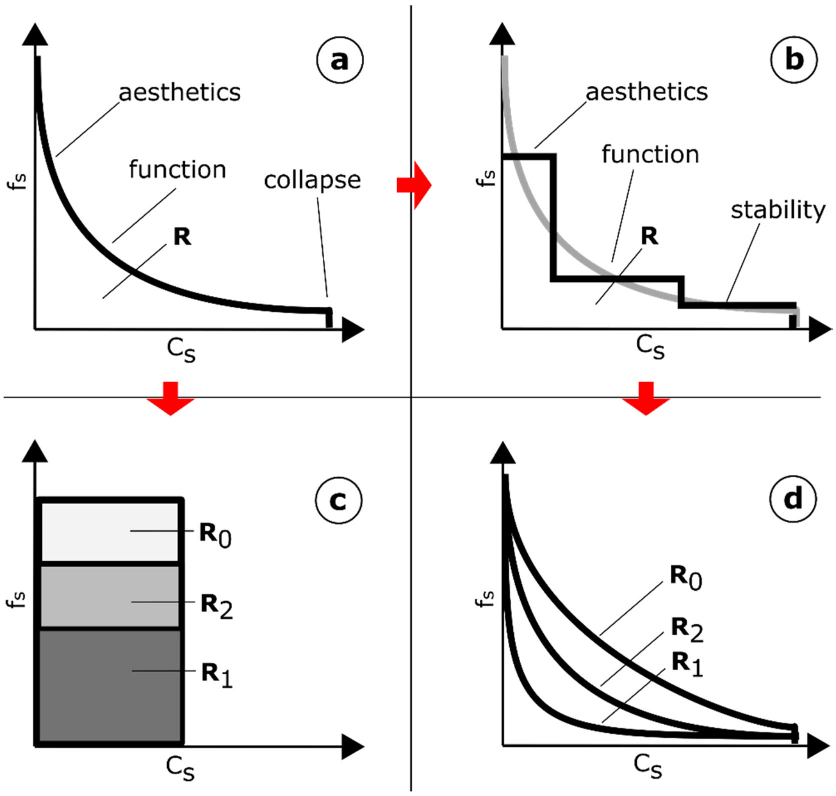

Figure 10 Risk (R) as a function of economic cost (C_s) and the probability of damage to a certain degree (f_s). In (a), the transition between different levels of damage (aesthetic, function and collapse) result in a continuous function. In (b), the continuous function is simplified to a step-wise function. In (c), a tolerability criterion introduces a cost for exceeding this limit, which means that only this cost is considered when calculating the risk for three alternatives (R_0, R_1 and R_2). In (d) the stepwise risk-function from (b) is considered instead, but since the calculation of R per building varies, the calculated risk for three alternatives have the shape of a continuous function.

Safety measures to prevent damage are also possible in this part of the cause-effect chain. Such measures can include the fortifying of foundations. This measure is, however, likely to be very expensive and is only feasible for individual buildings with a high risk of damage.

8 SUMMARY OF THE PUBLICATIONS

8.1 Paper I - Framework for risk assessment

The first paper (Sundell et al., 2015b) outlines a structured framework for risk assessment and management based on the current ISO standard (ISO, 2009) and the works by Aven (2012) and Lindhe (2010), see Figure 11. Several of the suggested procedures in the framework are commonly investigated in the planning phase of infrastructure projects in Sweden but often with fragmented and not clearly linked approaches for geological modelling, hydrogeology, geotechnics and risk. This fragmentation causes a need for a framework that describes how the different investigations in the cause-effect chain can be interlinked for a comprehensive risk assessment.

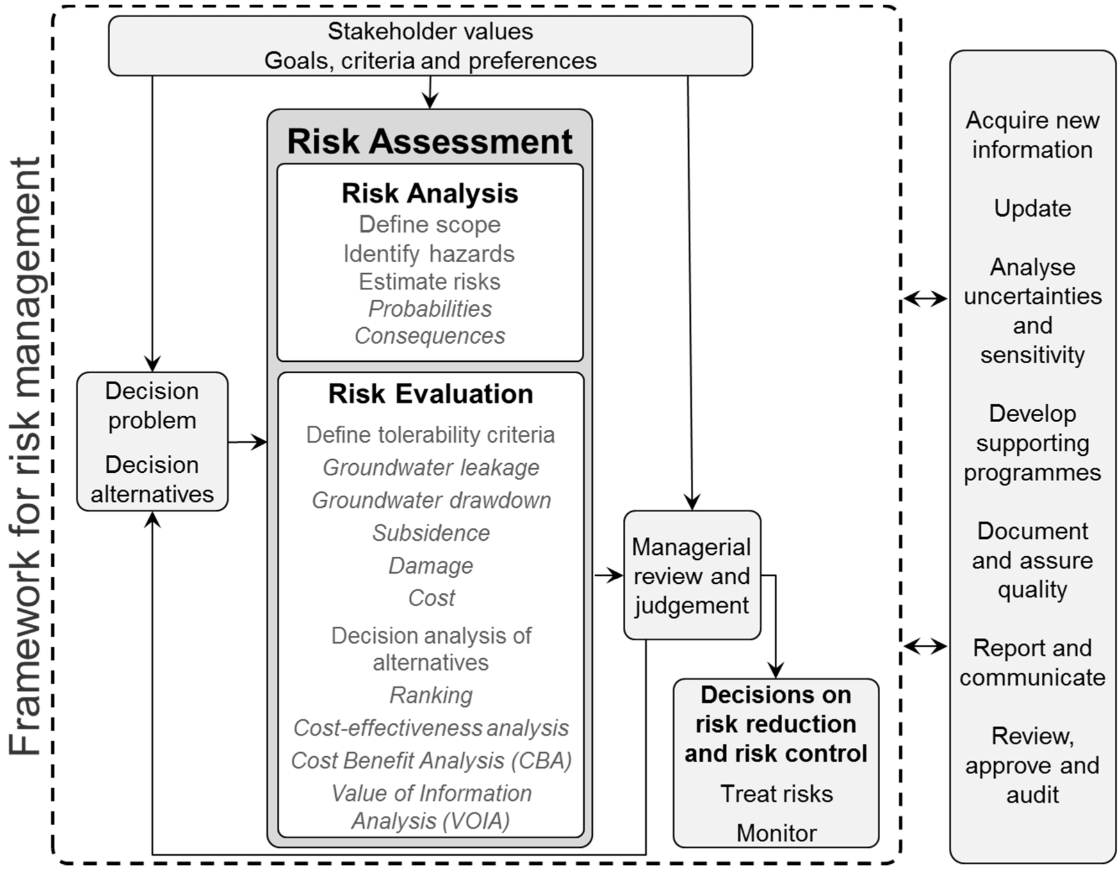

Figure 11 Framework for risk assessment, management and decision support modified after Publication I.

Five different modules necessary for the risk assessment are introduced in this paper (Figure 12). The first four modules relate to the cause-effect chain and the processes introduced in Section 2. Module 1 emphasizes the need for a probabilistic soil stratigraphy model for estimation of the likelihood of compressible sediments at locations with constructions sensitive to subsidence (further developed in Paper II). In module 2, suggestions for probabilistic groundwater modelling are introduced (further developed in Papers IV and V). In module 3, probabilistic subsidence modelling based on modules 1 and 2 and probability density functions (PDFs) of compression parameters are introduced (further developed in Papers III and IV).

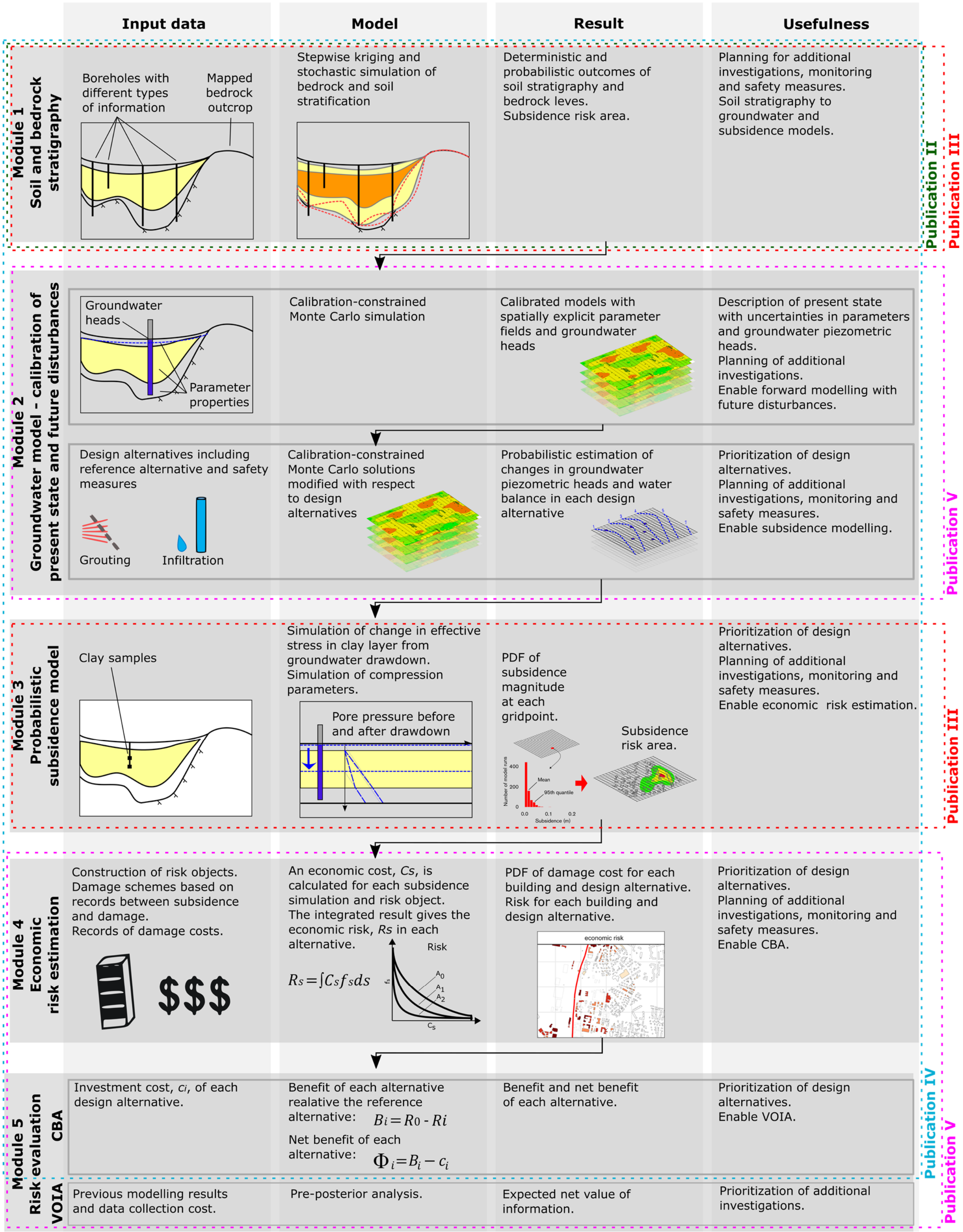

Figure 12 The five different modules for risk assessment together with their interlinkage. The modules are introduced in Publication I and further developed and applied in Publications II-V.

In module 4 (risk estimation), the calculated probability of damage of a certain degree, f_s, is combined with a cost function representing the economic consequences of subsidence, C_s. From these, the economic risk, i.e. the expected consequence cost for subsidence can be calculated as R_s. The four modules can be included in a risk analysis where the groundwater drawdown, subsidence magnitude and the economic risk is estimated.

In the fifth module (risk evaluation), the economic benefit of the different alternatives is calculated using CBA and the need for additional information is calculated using VOIA. The basic idea of VOIA is to value additional information as the change in expected total cost (or benefit) of the project due to new information, see Section 3. A CBA for design alternatives is conducted in Papers IV and V. A method that combines VOIA with probabilistic groundwater modelling is presented in Paper V.

Paper I provides a novel framework for risk assessment of groundwater drawdown-induced subsidence. The specific modules in this framework have then been further developed in the subsequent papers of this thesis.

8.2 Paper II – Probabilistic simulation of bedrock levels and soil stratigraphy

An essential part of describing the groundwater drawdown – subsidence – damage chain is a good understanding of the geological setting. In this paper (Sundell et al., 2016b), a novel method for probabilistic modelling of soil stratigraphy and bedrock level is presented.

The probabilistic soil stratigraphy method uses borehole logs with different types of information to build a model for bedrock levels and soil stratigraphy. Different information types include boreholes reaching and not reaching the bedrock, together with boreholes containing and not containing information on soil stratigraphy. The overall idea of the method presented is to use all available data that contains useful information on soil and bedrock stratigraphy in a probabilistic model. This is achieved through a combination of a stepwise kriging (see Section 4) procedure and statistical simulations in the R software environment (R Development Core Team, 2018). The modelling process is stepwise since this procedure takes account of different types of information and the dependencies between the different layers. If the layers were to have been simulated independently from each other, unrealistic layering could have been the result.

Building a geological soil stratification model in a city with thousands of boreholes can take a very long time depending on the method chosen. Some methods are based on linking boreholes together, see e.g. Peterson et al. (2014), which could be necessary if a detailed model in a heterogeneous environment is needed. If fewer details are acceptable, e.g. ignoring information on embedded layers, the method presented in Paper II is an efficient approach that is relatively easy to update when new information becomes available. The method in Paper II has proved to provide geologically reasonable results in real world applications applied in case studies in Stockholm (Sundell, 2015), Gothenburg, (Sundell et al., 2016a) and Varberg (Sundell et al., 2018). Minor modifications of the method to adapt to the conditions in the Varberg case study are presented in Paper IV. The method is useful and efficient in areas with relatively large amounts of available data and when the stratigraphy can be simplified to continuous layers. If this is not the case, other approaches, such as the ones presented in Section 4, could be considered.

The method provides a subsidence risk area, which is defined as areas where groundwater pressure in the confined aquifer is above the lower boundary of the clay layer. No subsidence and hence no damage are assumed to occur outside the risk area. The risk area is where groundwater drawdown can cause subsidence but there is no differentiation of the risk between drawdown magnitudes.

8.3 Paper III – Probabilistic subsidence model on a large scale

In Paper III (Sundell et al., 2017), the soil stratification model in Paper II is combined with a subsidence model. Firstly, a method for upscaling and quantifying variability in parameter values from soil samples to a large spatial scale is presented. Secondly, a probabilistic method for simulating subsidence on this scale is introduced. Finally, a subsidence risk area in which different groundwater drawdown magnitudes are taken into account is presented.

The risk of subsidence needs to be evaluated according to the potential future groundwater drawdown scale (km^2). Nevertheless, most calculation and investigation methods for geotechnical problems are developed for the scale of a construction project (10-1,000 m^2). On the larger spatial scale of groundwater drawdowns, it is very expensive to sample with the same frequency as in construction projects. To address this, a method for calculating subsidence on this scale together with a representation of uncertainties in the calculations has been introduced in this paper. The method is applied to a case study in Stockholm, Sweden with compression parameters calculated from 79 piston samples. In the first stage, compression parameters are transformed to normality and detrended against depth. Dependencies between parameters are considered by defining quotients between the dependent and the studied parameter. Although the 79 samples are spatially sparse, it is necessary to investigate if a sample is relevant for the investigated area. By dividing the samples into relevant groups based on e.g. location, expected load history and calculated sample disturbance, differences between these groups is investigated using ANOVA, see e.g. Marx and Larsen (2006). Since ANOVA requires normally distributed data with equal variances, the data is first detrended and transformed to normality. Equal means among groups define the null hypothesis (H0), which is rejected on a 0.05 significance level. For parameters with significant differences, unique PDFs for the different groups are defined.

From the PDFs of the parameters and the probabilistic soil stratigraphy model presented in Paper II, subsidence is simulated using the method presented in Section 6. The significance of individual parameters to the calculated subsidence is calculated using the Spearman rank correlation coefficient, see e.g. Bedford and Cooke (2001). When mapping the result of the sensitivity analysis, parameters that are most significant to the simulated subsidence at a certain location can be identified. The result of the subsidence simulation is used to draw a risk map where areas with a low probability of subsidence are separated from areas where there is a higher probability of subsidence. The risk area is defined as areas where the 95th percentile of the simulation of subsidence exceeds 2 cm (absolute subsidence) for groundwater drawdown magnitudes of 0.5, 1 and 2 metres. This means that the risk in the maps is expressed at a constant level of both consequence (2 cm subsidence) and probability (95th percentile). This definition introduces a tolerability criterion for subsidence (2 cm) defined for intermediate events (extent of the different groundwater drawdown magnitudes), as previously discussed in Section 3. The 2 cm limit is set from the damage schemes introduced in Section 7 of this thesis as being a lower limit where slight damage can occur.

The risk areas and the result of the sensitivity analysis can, together with information on sensitive constructions, be used to assist decision-making related to prioritization of risk- reduction measures, monitoring and further investigations.

8.4 Paper IV – Comprehensive Risk Assessment

In Paper IV, a comprehensive risk assessment of groundwater drawdown-induced land subsidence that facilitates cost-benefit analysis of risk-reduction measures is presented. It takes into account the entire chain of events, from initiation of groundwater drawdown to the resulting consequences. The novel aspect of this work is the combination of several probabilistic methods. The approach combines the soil stratification model presented in Paper II and the probabilistic subsidence model presented in Paper III with the inverse probabilistic groundwater modelling technique presented in Section 5 (PEST) to simulate total subsidence and subsidence after six months for different design alternatives. From the damage schemes introduced in Section 7, the severity of subsidence of different magnitudes is estimated. In contract to Paper III, the lower limit for damage is adjusted to 1 cm, and three instead of one damage categories are adopted from the above-mentioned schemes. Cost functions from historical records of subsidence damage cost in each category are then defined as PDFs. The combined result gives a high spatial resolution of probabilistic estimates of groundwater drawdown, subsidence and risk expressed as a combination of damage costs and probability for each alternative on the building scale. This result distinguishes building areas with significant economic risk of subsidence damage from low-risk areas in the different alternatives.

The preferable alternative is recommended by means of a complete CBA, where the criterion is maximum net benefit, see Section 3. Compared with the risk in the case of a reference alternative, the best prior alternative is identified as the alternative with the highest expected net benefit.

8.5 Paper V – Economic Valuation of Hydrogeological Information

In Paper V, a method for value of information analysis (VOIA) of additional hydrogeological information is introduced. The method combines the inverse probabilistic groundwater modelling technique presented in Section 5 (PEST) for uncertainty estimation of groundwater drawdowns of different design alternatives with a novel method for VOIA. In a prior analysis, the probability that a design alternative exceeds a tolerability criterion (defined from the risk areas in Paper III) is calculated from the groundwater model. The calculation of the cost for exceeding this criterion follows the principle introduced in Section 7. As in Paper IV, the alternative with the highest net benefit compared to a reference alternative is identified.

In a pre-posterior analysis, the benefits of expected uncertainty reduction deriving from additional information is compared with the cost of obtaining this information following the principle of VOIA introduced in Section 3. Compared to existing approaches for VOIA, the method can assess multiple design alternatives through the introduction of detection events and intervals where hydrogeological parameters are used as a proxy for failure. This results in the production of spatially distributed VOIA maps for identification of locations where additional information is (or is not) beneficial.

9 DISCUSSION AND FUTURE RESEARCH

The main contribution of the presented framework and methods in this thesis compared to existing approaches is (i) the ability to carry out a comprehensive risk assessment that considers uncertainties in all parts of the cause-effect chain and (ii) its large spatial scale. As stated in the limitations, the presented material can be seen as a toolbox where parts can be adapted, improved and replaced according to the needs of the situation. In this chapter there is a discussion of some main issues relative to the need of future research.

One of the main limitations of the presented methods is that only statistically quantifiable uncertainties are addressed comprehensively. Other sources of uncertainty, including model boundaries, structure and technical conditions, are not quantified. Instead, the limitations of these sources with regard to the degree of evidence between the forecast provided by the methods and the actual outcome of the future risk together with the method's potential for use as decision support are discussed in the different papers. When applying the methods in future studies, a combination of structured approaches for revision of the risk assessment are recommended to fill the gap created by uncertainty sources not included. Tools for such revisions include the NUSAP (Funtowicz & Ravetz, 1990) and the uncertainty matrix (Walker et al., 2003) methods introduced in Section 3.7. These revisions, together with the suggested methods, are expected to serve as transparent communication with stakeholders, provide the project owner with plausible scenarios, and identify the need for additional research, monitoring and safety measures.

The linked model presented in Paper IV is a combination of four different methods where different software has been used. This procedure works but is not considered to be very practical for the industry (consulting hydrogeologists). The user interface (UI) of the groundwater modelling software (GMS) includes tools for both geological modelling and subsidence but as of today these cannot be combined probabilistically. A combined approach for probabilistic geological, groundwater and subsidence modelling in the same UI would simplify modelling efforts and make the linked procedure more applicable in practice to industry.

As stated before, the geological model is only recommended at locations where the soil strata can be simplified into three continuous layers. If the clay layer is embedded with coarse-grained material, consolidation times can increase significantly. To handle these geological settings, the whole modelling procedure needs to be developed, where stratification is modelled using e.g. T-PROGS (Carle & Fogg, 1997). In the Varberg and Stockholm case studies, the clay layers are generally less than 10 m thick and an uncertainty of a few metres has a significant impact on the subsidence estimations. In many regions around the world where significant subsidence has been observed, the total clay thickness is much greater and the subsidence estimations can be expected to be less sensitive to an uncertainty of a few metres. If uncertainties in the geological model are assumed to contribute marginally to the total uncertainties, a deterministic instead of a probabilistic geological model can be implemented and parametrized probabilistically, as in the subsequent modelling steps of the methods presented in Paper IV.

In the groundwater model, only parameter uncertainties are addressed in the inverse probabilistic modelling. Other assumptions would be possible regarding the geological structure, boundary conditions, model size and resolution, decisions on which parameters to model probabilistically, assumptions of geostatistical properties of the heterogeneous parameter field, distance between pilot points, prior parameter estimates, and calibration data. When building the models for the Stockholm and Varberg case studies, a great deal of time and effort was spent on testing several different assumptions before set-ups that converged with inverse modelling were found. Despite these efforts, only one model set-up was calculated probabilistically in each case study. Although the probabilistic parameter fields can to some extent compensate for possible deviations in geological structure in the soil layers see reasoning regarding *K* and *T* in Paper IV), it is recommended that uncertainties in the location of fracture zones are investigated further. In addition to future studies of the influence of the bedrock characteristics, it is of interest to calculate the uncertainty contribution of different assumptions in an inverse probabilistic model, as recommended in e.g. Refsgaard et al. (2012). These evaluations should preferably be compiled independently by different modellers to avoid bias but using the same input data. It would also be of interest to calibrate the model using transient data from pumping tests and continuous observations and not just steady-state models as in the case studies. Transient calibration was tested in the case studies but despite the efforts made only inverse (and not probabilistic) calibration was successful. In both case studies, the availability of reliable hydrogeological input data has also been an issue since tests were difficult to evaluate and they revealed different results at short distances from each other. This was handled by not introducing fixed parameter values except at locations where reliable information can be assumed.

One main limitation of the subsidence calculations is that loads from buildings are omitted. In the initial work on the Stockholm case study in Paper III, a model that included structural loads was evaluated. This model estimated the weight of each building (about 500 buildings) within the model area based on general estimations of building material depending on the building category and construction year, gross floor area from maps, and the building height from a laser-scanned terrain model. The stress distribution in the soil from the buildings was then estimated using the Boussinesq's approximation. However, this calculation slowed down the probabilistic subsidence simulations significantly. When the building load in the case study was omitted, the deviation of the calculated subsidence was in general small and did not affect the extent of the risk area significantly. In the light of these results in Paper III, the load from buildings is omitted in subsequent studies. Instead, as recommended in

Paper IV, detailed studies of buildings with a significant risk of subsidence that includes building load and foundation are recommended. In both publications III and IV, the relatively large deviations in parameter values represent the actual soil heterogeneity (aleatory uncertainties) and uncertainties in sampling and evaluation (epistemic uncertainties). Investigations of sample disturbance on a local scale indicate significant differences between piston samples and larger block samples, where the latter result in larger OCR and stiffness values, which implies a forecast with smaller subsidence magnitudes (Karlsson et al., 2016). It is recommended that the differences resulting from bias in the sampling techniques be studied further, together with the issue regarding whether sampling uncertainties can be reduced by means of more accurate sampling and evaluation procedures.

As implied by the relationship between specific storage and compressibility (see Sections 5.1 and 5.8), groundwater flow and subsidence are interdependent processes. Since groundwater drawdown is modelled first and then connected to a subsidence model, the modelling approach is not fully coupled. A fully coupled approach would include stress-dependent storage and hydraulic conductivity properties of the aquitard when modelling the complete groundwater flow system. Although the SUB-WT package includes these stress-dependent processes when modelling subsidence, the package is not fully coupled with the MODFLOW model of the aquifer system (Galloway & Burbey, 2011). As discussed earlier, the vertical subsidence model does not account for horizontal strains and creep. In two reviews (Galloway & Burbey, 2011; Gambolati & Teatini, 2015) of existing modelling approaches of geomechanics and groundwater extraction, more advanced fully coupled finite-element codes that account for 3D deformation, including creep, are presented. As stated in the reviews, these codes are computationally very demanding. Combining these codes with inverse probabilistic groundwater models is presumed to be unfeasible in the lights of current computational constraints.

The current damage-cost model in Paper IV only considers building area and vertical subsidence magnitude and is thus a significant simplification of the actual response. Compilation of a detailed database of subsidence movements, building and foundation types and damage costs would improve this model.

It is recommended that the suggested VOIA method presented in Paper V is evaluated in other case studies, where the cause (leakage) and the effect (damage costs) are more closely related. It is also recommended that the VOIA model is evaluated for the comprehensive model of the cause-effect chain (presented in Paper IV) and not only for a model restricted to groundwater leakage and drawdown (as in Paper V).

All the above-suggested improvements to more advanced models are supposed to better represent the different processes in the cause-effect chain and hence reduce epistemic uncertainties. The need for these improvements can be discussed from a

VOIA perspective, comparing the cost of more advanced investigations and models with the expected benefits from reduced risk of making an erroneous decision. Another concern regarding more advanced models is securing assurance that these do not obscure stakeholder review and communication (Saltelli & Funtowicz, 2014). The presented modelling approach is useful in the early stages of a risk assessment to identify areas and buildings at risk and as a decision-support tool regarding the planning of additional investigations, monitoring and safety measures. An example of this usefulness is if the outcome of the model results in a limited number of buildings associated with high risks (as in Paper IV). Additional investigations and/or more advanced calculations can reduce uncertainties regarding these risks. If additional information can change the expectations of what is the best, i.e. the most profitable, alternative, then these investigations should be realized. If these investigations are limited in scale to a few buildings, computational constraints with more advanced numerical models are supposed to be less of an issue in comparison with the initial large-scale model. If additional investigations are not assumed to lead to other recommendations, the safety measures recommended in the initial assessment together with a monitoring programme should be realized in the highlighted risk area.

Even if the presented models are aimed at an early-stage risk assessment, the techniques are also assumed to be useful in the construction and operation stages of a project. During these stages, measurements of leakage, drawdown and subsidence, along with observations of damage, are typically done. The origin of subsidence damage to a building is not always clear despite measurement efforts. In addition to groundwater drawdown from an infrastructure project, the damage can be caused by a load from the building itself and increased stress levels from other nearby projects. Since the project owner holds the burden of proof, it is in his/her interest to find the reason for subsidence damage. Otherwise, the project owner might have to compensate for damage not caused by the infrastructure project. A coupled groundwater-subsidence model calibrated to available observations is assumed to be useful when identifying the reason for damage. At this stage, it is also possible that several models equally well represent the observations, which means that probabilistic approaches and evaluation of different assumptions should be realized.

Despite the above-mentioned limitations, several novel and useful methods have been presented in the work covered by this thesis. Compared to existing procedures in research and practice, specific novel aspects of this thesis work include the ability to take account of different types of borehole information and dependencies between layers when building a probabilistic bedrock and soil stratification model (Paper II). Another novel aspect is the combination of this model with a probabilistic subsidence model that considers uncertainties in compression parameters through statistical analysis with regression methods and ANOVA (Paper III). A third aspect is the combination of the previously mentioned methods with inverse-calibrated probabilistic groundwater modelling and risk estimation as a function of damage and cost in a CBA of safety measures (Paper IV). A final aspect is the combination of inverse-calibrated probabilistic groundwater modelling with a VOIA procedure that is able to account for multiple design alternatives and present the result spatially (Paper V).

The methods introduced in this research project are useful as decision support with regard to the two project risks of not taking action when action is needed and taking action when action is not needed. When assessing the risk of groundwater drawdown-induced subsidence, the whole cause-effect chain from leakage to the cause of subsidence damage needs to be considered. This consideration should recognize uncertainties in all parts, including soil stratification, groundwater leakage and drawdown, subsidence, building response and damage costs. For a comprehensive risk assessment in practice, different competences and stakeholders are needed. The material presented in this thesis can serve as a useful reference in future studies where different competences and stakeholders work together on comprehensive risk assessment procedures.

10 CONCLUSIONS

This research has resulted in improved multidisciplinary approaches for analysis and communication of the risk related to land subsidence due to groundwater drawdown. The overall aim of developing a framework for risk assessment as well as the four different objectives have been fulfilled:

- The overall aim to develop a framework for risk assessment of groundwater drawdown induced subsidence is fulfilled by the presentation in Publication I together with the methods presented in Publications II-V. This framework embraces the whole cause-effect chain for groundwater drawdown-induced subsidence. The presented framework provides a structure for identification, implementation and motivation of the most appropriate safety measure, given the chosen decision criteria. The presented framework also serves as a basis for connecting the specific objectives to the overall aim.
- The first specific objective, i.e. to develop a method for probabilistic modelling of bedrock levels and soil stratification, is met through the presentation in Publication II. The presented method is proven to efficiently combine different sources of information, handle large amounts of data of different character and quality, require little manual adjustments, be easy to update, and provide a geologically sound result when applied to case studies in Stockholm, Gothenburg and Varberg.
- The second specific objective, i.e. to develop a method for probabilistic modelling of groundwater drawdown-induced subsidence is met through the presentations in Publication III and is applied in Publication IV. The result of the simulation is presented in the form of risk maps, where the 95th percentile of 2 cm subsidence is suggested as a tolerability criterion. The maps have been used in a real-world situation for risk communication in the application for permit to drain groundwater in the City Link case study in Stockholm. If these maps are combined with information on the vulnerability of risk objects, such as buildings and installation, the maps provide useful decision support for the planning of safety measures, monitoring and additional investigations.
- The third specific objective, i.e. to develop an approach to comprehensive risk assessment that facilitates cost-benefit analysis of risk-reduction measures and considers the entire chain of events, from the initiating groundwater drawdown to the resulting consequences, is met through the presentation in Publication IV. The risk of subsidence damage is expressed as a function of probability of occurrence and damage costs for different design alternatives. The results include spatial probabilistic estimates of risk costs, which can be used to distinguish areas with significant risk from low-risk areas. The result also identifies the best prior alternative with the highest expected net benefit compared to a reference alternative. These results can be used as decision

support for prioritization of risk- reduction measures and identification of the need for further investigations and monitoring.

- The fourth specific objective, i.e. to develop a method for a value of information analysis of additional hydrogeological investigations when managing groundwater drawdown, is met through the presentation in Publication V. The method results in a prior analysis where uncertainties regarding the efficiency of safety measures are estimated, and a pre-posterior analysis where the benefits of expected uncertainty reduction from additional information is compared with the costs incurred to obtain this information. In comparison with existing approaches for VOIA, the method is able to assess multiple design alternatives, to use hydrogeological parameters as a proxy for failure, and to produce spatially distributed VOIA maps.

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