

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Improving the Practical Applicability of Groundwater Protection  
Methods for Small and Medium-Sized Supplies

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Gothenburg, Sweden 2026



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ISBN: 978-91-8103-396-0

Acknowledgements, dedications, and similar personal statements in this thesis,  
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Doktorsavhandlingar vid Chalmers tekniska högskola  
Ny serie nr 5853  
ISSN 0346-718X  
<https://doi.org/10.63959/chalmers.dt/5853>

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Cover: Illustration of stakeholders in discussion in front of a road sign marking a  
water protection area in Sweden

Chalmers Digital Printing  
Gothenburg, Sweden 2026



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## ABSTRACT

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Safe drinking water is fundamental to public health and societal development, and groundwater supplies around half of the world's drinking water. Yet these resources are under increasing pressure from agriculture, infrastructure development, climate change, and rising freshwater demand. This has increased the emphasis on preventive source protection rather than relying mainly on increasingly advanced treatment. Implementing such protection is far from straightforward. Effective groundwater protection must address both microbial hazards and contaminants from wider contributing areas, often creating tensions with existing land use and stakeholder interests. Although policy increasingly promotes catchment-based and risk-based approaches, their practical application remains difficult, particularly for small and medium-sized water supplies due to limited resources. At the same time, readily usable tools are often lacking, and the gap between hydrogeological science and practice continues to widen.

Against this background, this thesis aims to strengthen groundwater protection for drinking water by improving how scientific methods and knowledge are applied in practice, with particular focus on Sweden. Using a Design Science Research approach, it translates selected methods into practice-oriented approaches for everyday water protection work, with emphasis on ecosystem services, risk and uncertainty, groundwater modelling, cost-benefit analysis, and environmental justice.

The findings show that water protection can be strengthened by translating scientific methods into forms that are more usable in routine practice. Across the thesis, this is achieved by making uncertainty in protection zone delineation more explicit, broadening the assessment of what is at stake beyond the core drinking-water function, and creating more structured ways to connect risk, consequences, and economic reasoning in water protection planning. It also points to the importance of broader system perspectives, including environmental justice, in decision-making. The thesis further demonstrates how Design Science Research can support the development of implementable instruments for drinking-water protection, and why formalizing the design process matters for ensuring that what is developed is also useful in practice.

Key words: groundwater protection, drinking water, water protection area, small systems

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## LIST OF PUBLICATIONS

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### INCLUDED PAPERS

This thesis includes the following papers, referred to by Roman numerals:

- I. **Gärtner, N.**, Zamzami, M., Lindhe A. *Accessible Probabilistic Modeling of Wellhead Protection Areas for Small and Medium-sized Water Supplies*. Revision submitted to Discover Geosciences.
- II. **Gärtner, N.**, Lindhe, A., Wahtra, J., Söderqvist, T., Lång, L.-O., Nordzell, H., Norrman, J., Rosén, L. (2022). *Integrating Ecosystem Services into Risk Assessments for Drinking Water Protection*. Water, 14, 1180.
- III. **Gärtner, N.** (2026). *A tool for screening groundwater ecosystem services at Swedish drinking-water sources*. Vatten, 41, pp. 55-62.
- IV. **Gärtner, N.**, Söderqvist, T., Lindhe, A. *Applying Cost-Benefit Analysis to Water Protection Areas: An ecosystem services-based framework with probabilistic benefit estimation*. Manuscript.
- V. **Gärtner, N.**, Lindhe, A. (2026). *Disparities in drinking water services: Private well dependence and public supply inequities in Western Sweden*. Environmental Advances, Vol. 23, 100692.

## CONTRIBUTION TO THE PAPERS

The author has made the following contributions to the papers. The contributions are based on the CRediT guidelines (Contributor Roles Taxonomy).

<b>CRediT - Indicator</b>	<b>Definition</b>	<b>Paper I</b>	<b>Paper II</b>	<b>Paper III</b>	<b>Paper IV</b>	<b>Paper V</b>
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims.	<b>N.G.</b>	<b>N.G., A.L., T.S.</b>	<b>N.G.</b>	<b>N.G., A.L., T.S.</b>	<b>N.G.</b>
Data curation	Management activities to annotate, scrub data and maintain research data for initial use and later re-use.	<b>N.G., M.Z.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyse or synthesize study data.	<b>N.G., M.Z.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>
Funding acquisition	Acquisition of the financial support for the project leading to this publication.	A.L.	A.L., L.R., T.S., J.N.	A.L.	A.L.	A.L.
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.	<b>N.G., M.Z.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>
Methodology	Development or design of methodology; creation of models.	<b>N.G., M.Z.</b>	<b>N.G., A.L., T.S., J.W., L.R., H.N., J.N., L.O.L.</b>	<b>N.G.</b>	<b>N.G., A.L., T.S.</b>	<b>N.G.</b>
Project administration	Management and coordination responsibility for the research activity planning and execution.	<b>N.G., A.L.</b>	A.L.	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools.	N/A	N/A	N/A	N/A	A.L.
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components.	<b>N.G., M.Z.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team.	<b>N.G., A.L.</b>	A.L.	N/A	A.L.	A.L.
Validation	Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs.	<b>N.G., M.Z.</b>	<b>N.G., A.L., L.O.L.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation.	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>
Writing – original draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft.	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G.</b>
Writing – review & editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages.	<b>N.G., M.Z., A.L.</b>	<b>N.G., A.L., L.R., T.S., J.N.</b>	<b>N.G.</b>	<b>N.G.</b>	<b>N.G., A.L.</b>

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## ADDITIONAL PUBLICATIONS

The following scientific publication has been developed during the time of the PhD-studies but is not part of this thesis:

- A. Söderqvist, T., Wahtra, J., Nordzell, H., Hasselström Langer, L., **Gärtner, N.**, Norrman, J., Rosén, L., Lindhe, A. (2026). *Households' preferences to avoid disturbances in municipal drinking water supply: A nationwide contingent valuation study in Sweden.* Journal of Water Economics. 54, 1–24.
  
- B. **Gärtner, N.** *The Rapid Growth of AI and Machine Learning Publications in Hydrogeology Risks Widening the Gender Gap.* Revision submitted to Hydrogeology Journal.

## LICENTIATE THESIS

- C. **Gärtner, N.** (2022). *Advancing the Implementation of Protective Measures for Drinking Water Sources in Sweden* [Report no 2022:6]. [Licentiate Thesis, Chalmers University of Technology]. Chalmers University Publications Electronic Archive.  
[https://research.chalmers.se/publication/533320/file/533320\\_Fulltext.pdf](https://research.chalmers.se/publication/533320/file/533320_Fulltext.pdf)

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## ACKNOWLEDGEMENTS

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I would like to express my gratitude to some of the people who accompanied me on this journey.

First, I want to thank my supervisor Andreas Lindhe and my examiner Lars Rosén, for giving me the opportunity to take this journey, and for supporting me in finishing the dissertation from a distance.

I also want to thank my colleagues, who made this experience enjoyable through all the chats over coffee and lunch.

And thank you to my friends, especially Julia and Victor, who had to listen to my ramblings about all things water and not water, encouraged me throughout this process, and made sure that I did not take myself too seriously.

I am also grateful for the financial support I received from the Swedish Research Council for Sustainable Development (Formas), and the Swedish Drinking Water Network (DRICKS), which supported my PhD.

Finally, I want to thank my family. Emiliano, by simply being the joyful little tornado that you are, you always reminded me to close the computer and be done for the day. And Lorenzo, without your encouragement, I might never even have started this journey, much less finished it. Thank you for all your support, patience, and love.

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## ACRONYMS AND ABBREVIATIONS

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<b>Acronym or Abbreviation</b>	<b>Meaning</b>
AEM	Analytic element method
CBA	Cost-benefit analysis
CICES	Common International Classification of Ecosystem Services
DSR	Design Science Research
DWD	Drinking Water Directive
EC	European Commission
EPA	Environmental Protection Agency
ES	Ecosystem services
EJ	Environmental Justice
EU	European Union
GIS	Geographic information system
GW	Groundwater
GWD	Groundwater Directive
HACCP	Hazard Analysis and Critical Control Points
ISO	International Organization for Standardization
k	Hydraulic conductivity
MA	Millenium Ecosystem Assessment
MDWS	Municipal drinking-water supply
NPV	Net present value
TEEB	The Economics of Ecosystems and Biodiversity
TOT	Time of travel
WFD	Water Framework Directive
WhAEM	Wellhead Analytic Element Model
WHO	World Health Organisation
WHPA	Wellhead protection area
WPA	Water protection area
WPM	Water protection measure
WSP	Water Safety Plan
WSS	Water System Services

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# 1 INTRODUCTION

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## 1.1 Motivation

Reliable access to safe drinking water is a prerequisite for public health and human development. Around 50% of the world's drinking water is sourced from groundwater, making aquifers a critical part of drinking-water infrastructure (United Nations, 2022). At the same time, these resources are under growing pressure due to human activities, including infrastructure projects, agriculture, climate change, and the increasing demand for freshwater (Mekonnen and Hoekstra, 2016). The United Nations address this challenge through target 6.1 of the Sustainable Development Goals (SDGs), aiming for “universal and equitable access to safe and affordable drinking water for all” by 2030 (UN, 2015). Nevertheless, a wide range of contaminants are found in drinking-water sources (Benotti et al., 2009; Elliott et al., 2025; Gunnarsdóttir et al., 2025), and there is a strong call to protect source waters rather than relying on increasingly advanced treatment at drinking-water treatment plants (Lubick, 2008).

Protecting groundwater used for drinking water is, however, not straightforward. Historically, source protection often focused on microbial contamination, and it was considered sufficient to define a wellhead protection area based on a travel time criterion, for example a zone corresponding to around 100 days of groundwater transport, allowing pathogens to die off before reaching the abstraction point (WHO, 2006). While this approach remains relevant for certain hazards, it is increasingly insufficient in the face of contaminants that persist over long time periods or do not degrade in the subsurface, such as many industrial chemicals and so-called “forever chemicals”. In these cases, a narrow time-of-travel zone may not capture the full area that contributes water, and potential pollutants, to the well. As a result, effective protection often requires assessing the entire contributing area and the range of activities within it.

This broader protection perspective has important practical consequences. Considering the full contributing area typically implies larger protection zones, which increases the likelihood of conflicts with existing land uses and economic activities. Restrictions introduced for source protection can be contested by affected stakeholders, particularly

when the underlying assessments are perceived as uncertain or disproportionate. Because groundwater systems are heterogeneous and only partially observable, delineations of contributing areas and estimates of contaminant transport are inherently uncertain (Bhatt, 1993). Methods used to support protection zoning therefore need to acknowledge uncertainty explicitly, especially when their results inform decisions with wide-reaching social and economic impacts.

At the same time, implementation is not only a technical question. Preventive protection often provides benefits that are difficult to observe in the short term, because the main outcome is that contamination and related costs do not occur. In settings where drinking water is generally perceived as safe and reliable, additional restrictions can therefore be difficult to justify in the absence of incidents (Brouwer et al., 2020; Fineberg, 2013). This matters because acceptance of protection measures depends not only on risk estimates, but also on whether the value of the protected resource, and the benefits of protection, are made visible and understandable. Without such a basis, stricter land-use rules can be interpreted as unnecessary constraints on local development rather than as safeguards for long-term water security.

Recent European and Swedish policy developments reflect this wider understanding of source protection. Contemporary frameworks increasingly emphasise catchment-based and risk-based approaches that consider multiple hazards, pathways, and receptors, able to connect preventive measures to identified risks (e.g., Water Safety Plans (WHO, 2017a), the EU's Drinking Water Directive (EC, 2020) and the Guidelines from the Swedish Agency for Marine and Water Management (SwAM, 2021)). However, despite this policy direction, there remains a gap in practical guidance on how such approaches should be carried out in routine work in a way that is transparent and feasible under real-world constraints. In practice, this gap is most visible where resources are limited and where protection measures must be motivated to a wide range of stakeholders.

These challenges are amplified for small and medium-sized drinking-water supplies, which are common in Sweden and across the Nordic countries and often rely on groundwater, particularly in rural areas and municipalities with dispersed settlement patterns (Gunnarsdottir et al., 2020, 2017). Many of these smaller water suppliers operate with limited financial, technical, and human resources, which constrains their ability to carry out catchment assessments, update protection zones, and sustain monitoring, communication, and stakeholder processes over time (McFarlane and Harris, 2018; Rickert et al., 2016). This is important because small supplies can be more vulnerable to contamination events and are often overrepresented in reported outbreaks, even in high-income settings with generally strong water infrastructure (Herrador et al., 2016). As a consequence, advances in scientific understanding and policy ambition risk outpacing what is practically implementable in day-to-day protection work.

In summary, while the motivation and knowledge base for protecting groundwater used for drinking water have strengthened, practical implementation often lags behind. There is a need for methods, tools and approaches that are usable in practice while being able

to support the adoption of balanced decisions on protective measures across a range of hazards and local conditions and, importantly, can also help practitioners justify and communicate decisions by making the benefits of protection measures more transparent.

## 1.2 Aims and Objectives

The overall aim of this thesis is to contribute to *the protection of groundwater sources for drinking water* in small and medium-sized supplies *by improving the practical application of scientific methods and knowledge*, with a particular focus on the Swedish context.

The thesis applies a design science research approach to translate scientific theories, concepts, frameworks, and methods into practice-oriented approaches to address the challenges experienced by practitioners in small- and medium-sized systems.

To achieve the overall aim, the thesis has the following objectives:

- a. Identify practitioner needs in the Swedish drinking-water protection context, including legal, administrative, hydrogeological, and day-to-day practice conditions.
- b. Identify a suitable knowledge base of scientific concepts, theories, and methods that can address the needs of practitioners.
- c. Translate relevant elements of the knowledge base into practice-oriented methods, tools and approaches that are feasible for practitioners to apply.
- d. Evaluate through case studies and practitioner feedback the novel practice-oriented instruments.
- e. Reflect on the process and limitations of the method employed to develop novel instruments.

## 1.3 Thesis Structure

This thesis is organised into eight chapters, followed by the appended publications. Its structure reflects the logic of Design Science Research by moving from the problem context and knowledge base to the development, evaluation, and discussion of practice-oriented approaches for groundwater protection.

Chapter 1 introduces the thesis by presenting the motivation, overall aim, and research objectives. Chapter 2 presents the data that was used and collected for this thesis. Chapter 3 outlines the Design Science Research (DSR) methodology that provides the overall methodological framework for the thesis and explains how it is applied in this work.

Chapters 4 and 5 establish the foundation for the research. Chapter 4 describes the practical environment in which groundwater protection for drinking water takes place, with a particular focus on Sweden. It presents the historical background, the hydrogeological setting, the legislative and administrative context, and the current practice of implementing water protection areas. Chapter 5 presents the knowledge base

drawn upon in the thesis and introduces the main concepts, theories, and methods relevant to the work, including the Analytic Element Method, ecosystem services, risk and risk management, cost-benefit analysis, and environmental justice.

Chapter 6 describes the design and evaluation of the practice-oriented methods developed in the thesis. It explains how selected methods were adapted and refined to address identified practitioner needs and describes the role of practitioner input in the evaluation process. It then presents the main results of the thesis through the five appended papers and the practitioner survey. These include: probabilistic modelling of wellhead protection areas (Paper I), the integration of ecosystem services into risk assessments for drinking-water protection (Paper II), a screening tool for groundwater ecosystem services (Paper III), cost-benefit analysis for water protection areas (Paper IV), and an exploration of environmental justice in relation to drinking water services in Sweden (Paper V).

Chapter 7 discusses the overall contributions of the thesis, reflects on the selected methods and their limitations, and considers implications for future research and practice. The discussion is informed by input from a national practitioner survey, with responses from consultants, municipalities, water utilities, and County Administrative Boards used to contextualise the findings and support the recommendations presented in the chapter. Finally, Chapter 8 provides the concluding remarks.

Parts of this thesis build on work previously presented in the author's licentiate thesis (Gärtner, 2022).

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## 2 DATA

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**Data Used in the Individual Studies.** The studies included in this thesis rely primarily on secondary data. These data sources differ between the individual papers and include, for example, hydrogeological data, spatial data, national geodata, regulatory and planning documents, and socio-economic and drinking-water related datasets compiled from existing databases and public sources. No extensive primary data collection was carried out within the individual studies. More detailed descriptions of the data used, their sources, and any preprocessing steps are provided in the respective papers.

**Survey Data Included in this Thesis.** In addition to the data used in the individual studies, this thesis includes data from a practitioner survey on Water Protection Area (WPA) implementation in Sweden. The survey was designed to collect information on practitioner experiences, perceived challenges and needs in WPA work, familiarity with relevant tools and methods, and views on the relevance and usability of the approaches developed in the thesis. The target group comprised practitioners involved in WPA implementation and related drinking-water protection tasks, including staff from municipalities, County Administrative Boards, drinking-water utilities, and consulting companies. The survey was distributed using purposive sampling through direct email invitations to relevant contacts and practitioner networks, an invitation shared during a practitioner meeting, and a notice in the Swedish drinking water network (DRICKS) newsletter. It was open from 1 November 2025 to 31 December 2025 and generated 49 responses.

The survey was administered online using Microsoft Forms and consisted of 28 questions combining closed-response items with open-ended questions. Two versions of the survey were used to reflect different professional roles. The consultant version included additional questions on modelling and other technical tasks commonly carried out in consultancy assignments, as well as questions on perceived implementation needs and constraints. The implementer version, distributed to respondents working primarily in municipalities, water suppliers, and authorities, placed greater emphasis on process-related aspects, including how technical results are reviewed, interpreted, and used in decision-making. Responses were collected anonymously, with no directly identifying information recorded other than organisation type. The quantitative responses were

compiled as descriptive data, while the qualitative responses were grouped thematically according to the topics addressed in the survey. The survey results are summarised in Chapter 6.7, and the full survey materials and condensed responses are included in Appendix A and B.

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## 3 DESIGN SCIENCE RESEARCH METHODOLOGY

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### 3.1 Design Science Research Framework

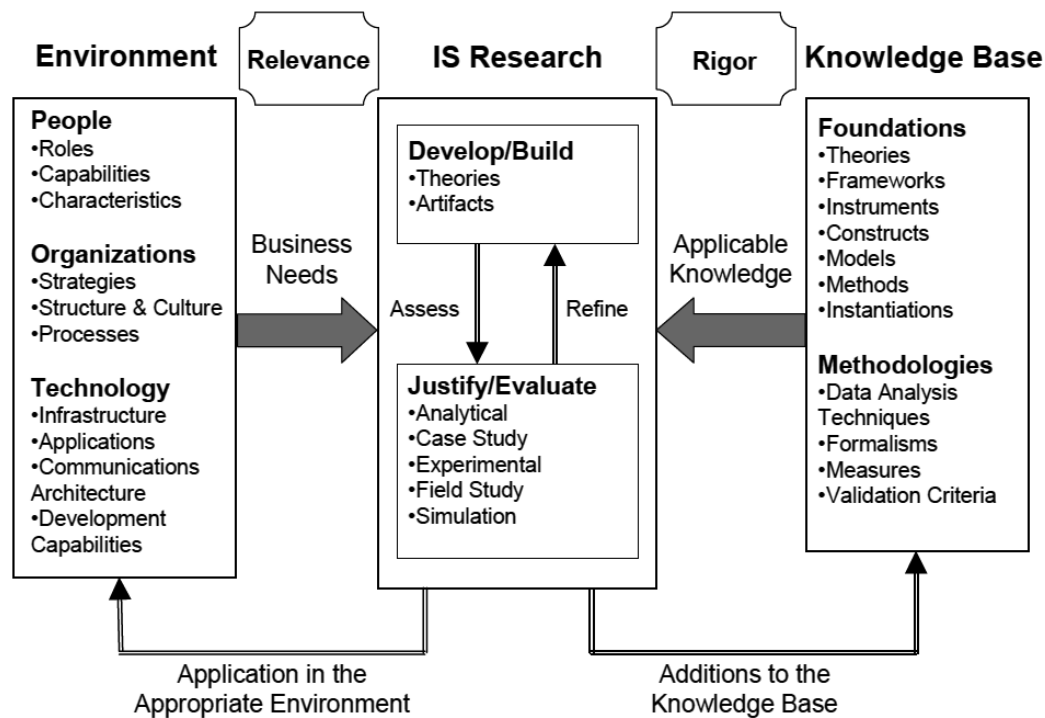
Design Science Research (DSR) originates from the broader design science tradition associated with Herbert A. Simon's argument that research can legitimately focus on the purposeful design and study of human-made artifacts (Simon, 1996, 1988). In its modern methodological form, DSR was later formalised within Information Systems research, particularly through foundational work by March and Smith (1995) and Hevner et al. (2004), and further operationalised through process-oriented guidance such as Peffers et al. (2007). In essence, DSR is a research approach in which the main contribution is the design and evaluation of an artifact that addresses a real-world problem, together with clear reasoning and evidence about how and why the artifact performs (March and Smith, 1995; Hevner et al., 2004).

DSR is most strongly established in Information Systems (IS) and Information Technology (IT), where research frequently aims to create practical solutions such as decision-support systems, data-driven workflows, algorithms, and organisational processes that interact with technology. A defining motivation is the dual expectation that research should be practically useful while remaining rigorous enough to contribute to a cumulative knowledge base. DSR addresses this by treating relevance and rigor as integrated parts of the same research logic rather than as competing goals (Hevner et al., 2004). For this reason, DSR is also increasingly taught and discussed as a structured approach for developing effective, demonstrably useful research outputs (Pastor et al., 2024).

A central concept in DSR is the artifact. Depending on the study, an artifact can be a method, model, workflow, framework, guideline, prototype tool, or decision-support approach. What makes it a DSR artifact is not its format, but the way it is treated: it is deliberately designed to meet stated objectives, grounded in prior knowledge, and evaluated against explicit criteria. The knowledge contribution is therefore not only that an artifact exists, but also the articulated design rationale and the evidence gathered through evaluation, including assumptions, trade-offs, strengths, and limitations. DSR is

often summarised as a build-and-evaluate logic, where development and evaluation are iterated and linked to justification and learning.

This logic is commonly illustrated using the Information Systems Research Framework (see Figure 1). The framework places the DSR activity between an environment on one side and a knowledge base on the other. The environment represents the practical setting in which a problem exists and in which an artifact is intended to be used. The knowledge base represents what can be drawn on, such as theories, models, methods, constructs, and established validation criteria. The DSR activity itself centres on iterative development and evaluation. “Develop/build” refers to designing the artifact by selecting, combining, and implementing design components. “Justify/evaluate” refers to assessing the artifact against its objectives using suitable evaluation forms, for example analytical evaluation, case study, experiment, field study, or simulation, with results feeding back into refinement.



**Figure 1.** Information Systems Research Framework illustrating Design Science Research as an iterative build and evaluate cycle situated between the environment (problem context and requirements) and the knowledge base (existing theories and methods), including the relevance and rigor cycles (from Hevner et al., 2004).

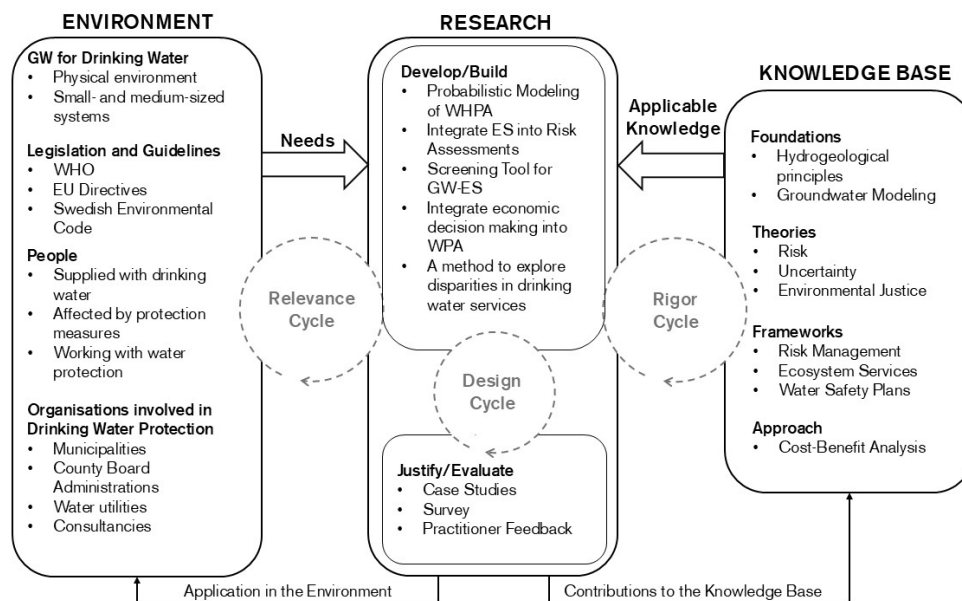
A key feature of the framework is that it makes two additional cycles explicit: the relevance cycle and the rigor cycle (Hevner et al., 2004). The relevance cycle links the research to the environment by grounding the work in real needs and constraints and by clarifying what success means in practice. The rigor cycle links the research to the knowledge base by ensuring that the artifact is informed by established theory and prior methods rather than being an ad hoc one-off solution. Together with the central design cycle (build and evaluate), these cycles describe how DSR can produce both a practically

applicable artifact and a defensible scientific contribution that can be reused, adapted, and tested in other settings.

Later developments of DSR have proposed extensions to the original framework. Drechsler and Hevner (2016), for instance, introduce a fourth change and impact cycle intended to account for dynamic application contexts and broader artifact-induced change. In this thesis, however, the three-cycle framework of Hevner et al. (2004) is considered sufficient, as the work is centred on the development and evaluation of groundwater protection approaches in a comparatively structured problem setting.

### 3.2 DSR Framework for Groundwater Protection

Including DSR in water resources management is still relatively new, and only a limited number of studies explicitly follow the methodology in water engineering contexts. Recent examples include work by Cerutti and colleagues, who used DSR logic to develop decision-support artifacts for groundwater protection and source protection actions in Canada (Cerutti et al., 2023, 2019), and Ge et al. (2024), who apply decision-support development to strengthen sustainability-oriented decision making. While rooted in Information Systems, these studies illustrate how DSR can be transferred to applied domains where complex real-world decisions require methods that are both technically credible and operationally usable. This is particularly relevant in water management, where Borowski and Hare (2007) have shown that researchers and water managers often operate under different incentives, time horizons, and expectations of what model-based tools should deliver in practice. Against this background, DSR becomes relevant because it provides a more formal structure for taking such practice conditions into account during artifact development and evaluation.



**Figure 2.** Design Science Research framework as applied in this thesis, showing the practical environment, the knowledge base, and the central research activities of develop/build and justify/evaluate, linked through the relevance, rigor, and design cycles.

In this thesis, I employ the Design Science Research (DSR) framework to develop a set of interrelated artifacts intended to support groundwater protection for drinking water supplies. Here the DSR framework focuses on several methodological, analytical, and decision-support contributions which are developed and evaluated in relation to a shared practical problem domain. Figure 2 illustrates how the Information Systems Research Framework was adapted to the context of this thesis and how the work is positioned between the practical environment and the scientific knowledge base.

The practical Environment refers to the context of groundwater used for drinking water, with attention to the physical conditions and the challenges associated with small- and medium-sized supplies. It is further shaped by the national and international legislation and official guidance, including WHO principles, European directives, and the Swedish Environmental Code. In addition, the Practical Environment includes the people and organisations affected by or involved in drinking water protection, such as consumers supplied with drinking water, land users affected by protection measures, municipalities, County Administrative Boards, water utilities, and consultancies. Together, these actors define the practical challenges to be addressed in the thesis, the requirements that the artifacts must satisfy, and the constraints under which they must operate.

The Knowledge Base provide the conceptual and methodological basis for the design of the artifacts and ensure that the work is grounded in prior research rather than developed as an isolated practical solution. It includes hydrogeological principles and groundwater modelling as well as concepts related to risk, uncertainty, and environmental justice. It builds on established frameworks such as risk management, ecosystem services, and Water Safety Plans as well as the methodology of cost-benefit analysis.

At the centre of the DSR framework is the research activity itself, which is organised as an iterative develop/build and justify/evaluate process. The develop/build component in this thesis comprises five main artifact-oriented contributions: a probabilistic approach for modelling wellhead protection areas (WHPA), an approach to integrate ecosystem services into risk assessments, a screening tool for groundwater ecosystem services, an approach for integrating economic decision making into water protection area processes, and a method for exploring disparities in drinking water services. These artifacts differ in form, but all are intended to support analysis, decision making, or practical implementation in groundwater protection. In this sense, the thesis does not produce one single end product, but a family of related artifacts that respond to different but connected needs within the same problem domain.

The justify/evaluate component is addressed through case studies, surveys, and practitioner feedback. Evaluation in this thesis is therefore not limited to technical performance alone, but also considers usefulness, applicability, clarity, and relevance to practice. This is consistent with the view in the DSR literature that evaluation should generate learning about both the strengths and limitations of the artifact and provide a basis for refinement (Venable et al., 2016). The design cycle shown in Figure 2 reflects

this iterative logic, in which development and evaluation inform one another throughout the research process.

The relevance cycle links the research to the environment by ensuring that the artifacts respond to real needs in drinking water protection practice. Four real needs in drinking water protection practice were selected for this thesis. The rigor cycle links the research to the knowledge base by grounding design choices in existing theories, frameworks, and methods. At the same time, the thesis contributes back to the knowledge base by adapting and combining these concepts in a groundwater protection context and by generating evaluated knowledge about how such artifacts can be designed and applied.

Overall, the DSR framework provides the methodological structure for the thesis. It clarifies how the research moves from problem context and prior knowledge to artifact development and evaluation, and how the resulting contributions aim to be both scientifically grounded and practically useful.



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## 4 DSR FRAMEWORK – ENVIRONMENT

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*This chapter illustrates the practical setting in which groundwater protection for drinking water occurs in Sweden. It addresses four themes including (i) the historic evolution of water protection from early technical and legal safeguards to modern protection zones, (ii) the types of groundwater sources available in Sweden and their use for drinking purposes, (iii) the legal and administrative rules that govern water protection areas (WPA), and (iv) the practice of WPA implementation. The last section summarizes the needs that arise from the environment.*

### 4.1 History of Drinking Water Protection

As humans settled into cities and early civilisations developed, communities began to convey water from sources outside the city walls. Reliable delivery of safe water is often described as one of the drivers of state formation, and collective water management helped bind communities together (Manuel et al., 2018). Alongside the technical measures required to secure water supply, early societies also developed rules to prevent contamination and to protect the source itself.

The earliest manufactured subsurface water-conveyance systems are often associated with qanats, which were developed roughly 6,000 years ago in present-day Iran. Qanats are subterranean tunnels that transport water from uplands to plains and settlements. They are typically excavated from the outlet area towards the source, connecting to a so-called mother well (Manuel et al., 2018). The construction and operation of qanats relied not only on technical knowledge but also on institutional arrangements for water management, including legal rules attributed to the era of the Babylonian King Hammurabi around 2000 BC (Gholikandi et al., 2013). These rules include obligations for landowners to safeguard surface sections above the qanat, liability for damage due to negligence or malice, and compliance with community rules (Gholikandi et al., 2013). Although no explicit dimensions for protection areas are described, the underlying idea of protecting source water along its pathway was clearly present.

For the Romans, fresh water was a resource that should be controlled and managed for the benefit of all (Bannon, 2017). Cicero listed running water (*aqua profluente*) first among the common goods that all humans share (Bannon, 2017). One of the most well-known Roman achievements in water technology is the aqueduct, a watercourse that carries water, mainly above ground, from the source to its destination. During Roman times, aqueducts and related water facilities were protected by law, and specific protection measures were defined. To protect transported water against contamination, buffer zones between private properties and aqueduct infrastructure were enforced. Within these zones, it was not allowed to plant trees or build, for example within 10 feet on each side of the structure (Frontinus, 100AD).

Roman regulations also addressed protection at the source. In *De aquaeductu* (*engl. on aqueducts*) written by the Roman engineer and water commissioner Sextus Julius Frontinus, circular protection areas are described around springs, together with prohibited activities in their immediate vicinity. For example, around springs a protection zone of 4.5 m is specified, and it was forbidden to construct, establish a place, plough or sow, or introduce anything into that area. Furthermore, it was strictly forbidden to graze livestock, cut hay or grass, remove brush, or disturb the natural vegetation layer. A fine would be collected if these statutes were not followed, and distributed equally to the accuser and the state treasury. A translation of *De aquaeductu* can be found online, see Frontinus (100AD).

With the fall of the Roman Empire and the beginning of the Middle Ages, water management and sanitation practices in many places declined, and source-water protection measures largely fell into oblivion. Water sources remained a common good, but they were often degraded through the way of life and daily activities of inhabitants (Ewert, 2007).

In the 19<sup>th</sup> century, the understanding that pathogens in water can cause disease, and that water-borne illness can be reduced through improved water management, re-entered scientific and public discourse. A well-known example is the work of Dr John Snow, who in 1855 linked a cholera outbreak in London to a sewage-contaminated well (US-EPA, 1999).

In the 20<sup>th</sup> century, growing scientific understanding of contamination and public health risks was increasingly translated into formal regulation. In this context, the United States and Germany were among the early countries to develop legislation and guidance relevant to water protection areas (Doveri et al., 2016). In the United States, the Federal Water Pollution Control Act of 1948 was one of the first major federal laws addressing water pollution (US-EPA, 2021). This was followed by the Safe Drinking Water Act, which became effective in 1974 and established a regulatory basis for protecting public drinking water. In 1986, the Wellhead Protection Program was added to the Safe Drinking Water Act, requiring states to protect underground drinking-water sources from contaminants that could harm human health. Germany introduced similar protective ambitions through the Federal Water Act of 1957, which regulated, among other aspects, pollutant discharges to groundwater.

Over the following decades, similar regulatory approaches spread beyond these early pioneers. Today, many countries regulate drinking-water quality through national legislation and associated guidance, and international frameworks provide common reference points for how drinking-water safety and source protection should be managed. The World Health Organization (WHO) publishes the Guidelines for Drinking-water Quality, which provide health-based recommendations and promote Water Safety Plans as a preventive, catchment-to-consumer approach to risk assessment and risk management that is increasingly adopted as best practice (Davison et al., 2005). In Europe, the EU Water Framework Directive establishes an integrated framework for protecting waters, while the recast EU Drinking Water Directive strengthens requirements for water intended for human consumption and embeds a risk-based approach across the supply chain.

Beyond unintentional contamination, water sources have also been deliberately targeted in conflicts since ancient times and have, in some cases, been used as a weapon. In 600 BC, Assyrians poisoned their enemies' wells with rye ergot fungus, leaving them hallucinating, intoxicated, and unable to fight back (Del Giacco et al., 2017). Emperor Barbarossa is reported to have hurled decomposing human bodies into enemy wells (Lindeke, 2018). Since the 20<sup>th</sup> century, knowledge about harmful substances and pathways of contamination has become extensive and widely accessible, which also implies a persistent risk of deliberate source-water contamination. This adds another motive for protecting sources and reinforces the need for adequate protection zones and measures. Today, many source-water protection plans include measures that address sabotage and deliberate attacks.

Overall, the historical examples illustrate that drinking-water protection has long combined technical solutions with rules that limit activities near water sources and along conveyance routes. Over time, the motivations and scientific basis for protection have shifted, from preventing visible contamination and water-borne disease to addressing persistent chemicals, complex land-use pressures, and broader societal risks. Despite these changes, a recurring theme remains that effective protection depends on enforceable measures that are perceived as justified, and that can be implemented under the practical conditions of the time and place.

## **4.2 Groundwater Used for Drinking Water in Sweden**

### **4.2.1 Hydrogeology in Sweden**

Hydrogeology in Sweden is highly heterogeneous, shaped by the combination of Precambrian crystalline bedrock and a landscape dominated by Quaternary glacial deposits. As a result, groundwater resources used for drinking water occur in several distinct aquifer settings, with large contrasts in storage, permeability, and typical well yields. Recharge is generally positive because precipitation exceeds evapotranspiration, but it varies strongly in space and season due to snow accumulation and snowmelt,

frozen ground, and the permeability of soils and sediments. These differences in aquifer type and recharge also translate into different vulnerability and groundwater-quality patterns, which is why a basic hydrogeological overview is essential when discussing drinking-water protection in Sweden. The main types of aquifers in Sweden are based on the classification of Knutsson (2008).

**Fractured aquifers.** In Sweden, the most widespread aquifers are fractured aquifers in Precambrian crystalline bedrock (the Baltic Shield). Groundwater storage and flow are restricted to fractures and fracture zones, so overall porosity is low (total fracture porosity typically less than about 1%, with effective porosity even lower), and well yields are often modest. Hydraulic properties vary strongly with rock type and fracture connectivity where granites tend to be more brittle and can host better-developed open fractures than gneisses or many basic rocks, but the key high-yield targets are usually fracture and fault zones with higher conductivity. Near the surface, glacial loading and frost action have enlarged fractures (tens of metres), while fracture frequency and aperture generally decrease with depth, although conductive zones can still occur at depth and dominate regional flow and well performance.

**Porous aquifers.** Sweden's main porous aquifers are Quaternary sand and gravel deposits, especially glaciofluvial eskers and deltas. These can be very permeable (typical  $K$  in the range  $10^{-4}$  to  $10^{-2}$  m/s for well-sorted gravel and sand), often form regionally extensive aquifers (tens to 100+ km long; commonly 10–100 m thick), and can support large springs and high-yield wells. However, even where transmissivity is high, sustainable yields can be limited by recharge and storage, which is one reason artificial recharge has been used in Sweden. A more common but generally lower-permeability porous material is glacial till. It is heterogeneous and may include sand and gravel lenses or fissility that locally increases flow and spring discharge, but its bulk conductivity is typically low and it more often supports small-scale supplies.

**Fractured porous aquifers.** Fractured porous aquifers combine intergranular pore space with fractures, typical of consolidated limestones and sandstones that are only slightly tectonized. In Sweden this is most important in the south, especially Scania, where Cretaceous and Danian limestones and associated sandstones can show low-to-medium matrix permeability but much higher effective permeability where fracturing (including glacially induced fracturing in the upper part) provides secondary porosity. These settings can produce comparatively high well capacities for Swedish conditions (reported median capacities exceeding about 17 L/s and up to roughly 55 L/s in parts of Scania). Cambrian sandstones in southern Sweden are another example, with moderate conductivities and village-scale well yields.

**Karst aquifers.** Karst aquifers in Sweden are less extensive than in many warmer regions because dissolution is less favoured by the cold-temperate to boreal climate, but they still matter locally and regionally in carbonate terrains. Even modest karst development in Swedish limestones can strongly enhance infiltration and create fast, channelised flow paths to springs. A hallmark is highly variable discharge: karst systems can drain very

large volumes rapidly during snowmelt or flood conditions but have low flows in dry periods, with extreme seasonal contrasts documented for Swedish karst.

**Groundwater recharge in Sweden.** Sweden spans cold-temperate maritime conditions in the southwest, cold-temperate continental conditions in the south, and boreal (sub-arctic) conditions further north; overall it is humid because annual precipitation exceeds evapotranspiration. Precipitation is typically 500–1000 mm/year, but can be as low as 300–400 mm/year in rainshadow areas east of the Scandinavian mountains [ref]. Recharge is strongly seasonal because winter precipitation accumulates as snow and produces intensive recharge during and after snowmelt; snow cover lasts about 1–2 months in the south, 4–6 months in central Sweden, and up to 7–8 months in the north (longer in high mountains), while frozen ground and local permafrost reduce infiltration and increase runoff. Long-term recharge varies widely with soils and bedrock: reported Swedish values range from ~280 mm/year in sandy soils to ~20 mm/year where compact till overlies crystalline rock, and down to only a few mm/year at hundreds of metres depth in bedrock; intermediate examples include ~160–200 mm/year in shallow sandy till or eskers and ~100–120 mm/year in fractured gneiss (Knutsson, 2008).

**Groundwater quality.** Swedish groundwater quality reflects both human pressures and natural geology. Reported issues include coastal salinity and chloride contamination (notably from road de-icing and other infrastructure-related sources), as well as nitrate and pesticide impacts in agricultural areas. In crystalline bedrock, deeper groundwater can be very old and saline, and near the Baltic Sea it can reflect mixed origins shaped by glaciation history, land uplift, and water–rock and microbial processes. Key naturally driven problem parameters in bedrock wells include radon and uranium, while other recurring issues are low pH and alkalinity in acidic terrains (with legacy effects from acid rain), plus elevated fluoride and locally arsenic. More recently, per- and polyfluoroalkyl substances (PFAS) has become a major concern in Sweden, especially linked to historical firefighting-foam use at fire-drill/training sites and airports, where contamination can be present in the groundwater (Ahrens et al., 2016).

#### 4.2.2 Small- and Medium-Sized Systems

The definition of a small or medium-sized water supply differs across and within countries. It is often set in legislation and based on criteria such as population served, volume of water supplied, number of service connections, or supply technology.

At EU level, very small supplies delivering less than 10 m<sup>3</sup>/day on average or serving fewer than 50 people are exempt from the Drinking Water Directive 98/83/EC, provided they are not used for commercial purposes (European Parliament, 2020). Beyond this exemption threshold, “small” is often used in EU reporting for supplies serving fewer than 5,000 people or producing less than 1,000 m<sup>3</sup>/day. In practice, this implies that everything above these thresholds is treated as “large” in reporting. This grouping is broad and combines systems with very different resources and organisational capacity, from small municipal supplies to large utilities. There is no harmonised EU definition of

“medium-sized” supplies, although definitions are used in the literature; for example, Bennich et al. (2025) define medium-sized supplies as serving 10,000 to 100,000 people.

For this thesis, a practical working definition of a medium-sized drinking-water supply is a system serving roughly 5,000 to 50,000 people and/or producing about 1,000 to 10,000 m<sup>3</sup>/day. This places it above the commonly used “small” reporting cut-off while remaining below the threshold where the recast EU Drinking Water Directive requires Member States to ensure leakage assessment covers at least suppliers serving 50,000 people or supplying 10,000 m<sup>3</sup>/day (Directive (EU) 2020/2184, Article 4(3)).

However, small and medium-sized supplies are not distinguished from larger systems by size alone, but also by their administrative, managerial, and operational realities and the challenges that follow from them. In practice, systems can be grouped by two features: who is responsible for administration, management, and operation, and who the users are. This includes (i) private or individual wells, such as boreholes, dug wells, or springs, typically serving a single household or a few households and operated by the users; (ii) community-managed supplies, run by the users themselves (for example, cooperatives), ranging from simple point sources where water is collected to more complex systems with treatment, storage, and piped distribution; and (iii) public supplies, managed by a public entity (such as a municipality) that provides drinking water within a spatially limited area (for example, a small town or municipality). The supply types and size classes used in this thesis are summarised in Table 1.

**Table 1.** Supply types and working size definitions used in this thesis.

	<b>Type of supply</b>	<b>Size</b>	<b>Size definition</b>
<b>i</b>	Private Wells	Small	One household or a few households
<b>ii</b>	Community managed supplies	Small	Minimum 10 households
<b>iii</b>	Municipal supplies	Small	< 5000 people or 1000m <sup>3</sup> /d
	Municipal supplies	Medium-sized	> 5000 people or 1000m <sup>3</sup> /d , but < 50000 people or 10000m <sup>3</sup> /d

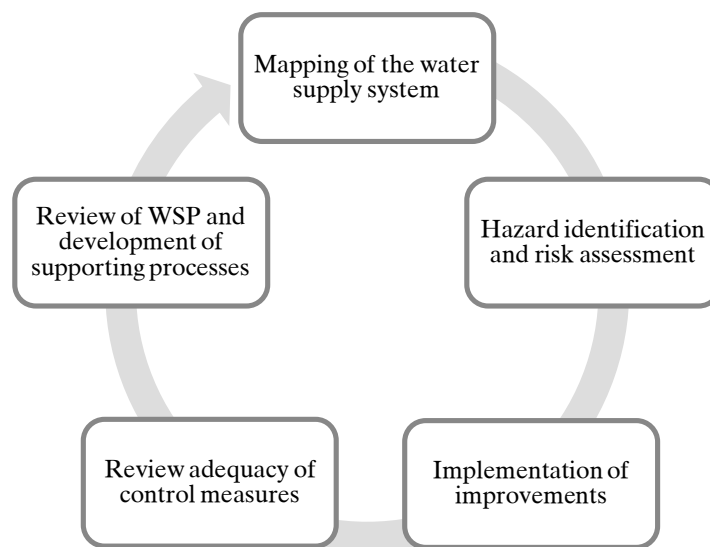
### 4.3 Regulatory Context: Rules, Regulations and Guidelines for Drinking Water Protection

Drinking water protection is shaped by a regulatory context that spans multiple levels, from international frameworks and European Union legislation to national law and practical guidance. It also includes different types of instruments, ranging from legally binding rules, such as directives, laws, and regulations, to non-binding guidance and handbooks that support implementation in practice. Together, these instruments define responsibilities, procedures, and expectations for how drinking water resources should be protected. Within this broader framework, recent developments have increasingly emphasised preventive and risk-based approaches to drinking water protection,

particularly through more systematic assessment of hazards and measures across the water supply chain.

### 4.3.1 WHO's Water Safety Plans

The World Health Organization (WHO) recommends the development of Water Safety Plans (WSPs) as a framework to ensure safe drinking water (WHO, 2022, 2017b, 2010). WSPs are built around proactive risk assessment and risk management and aim to identify hazards and hazardous events, evaluate risks, and define control measures across the drinking water system (see Figure 3).



**Figure 3.** Implementation cycle of a water safety plan after (after WHO, 2010)

WSP guidance covers the full “catchment to consumer” chain and supports a multiple-barrier approach. However, WSPs are not designed as a detailed method for delineating statutory protection zones or drafting local land-use restrictions. Instead, they provide a system-level framework for identifying risks and managing them through control measures at different points in the supply chain, including at the abstraction, treatment, and distribution stages.

The WSP approach builds on principles from Hazard Analysis and Critical Control Points (HACCP) and other systematic management approaches. HACCP is a preventive management system that addresses safety by analysing hazards and identifying points where control is essential (FDA, 2022). This concept, originating in the food sector to achieve food safety, has been applied to drinking water (Havelaar, 1994) and represents the foundation of WSP. However, due to the nature of HACCP, it is most suitable in the production part of the drinking water system (i.e., the drinking water treatment plant or supply). It is important to note that, even though WSPs are not specifically adapted to suit detailed assessments of source water protection, the basic concept is useful and emphasizes the importance of a risk-based approach.

### 4.3.2 The European Union's Directives

Several EU directives shape how source water protection measures are motivated and implemented. The most direct one for drinking water is the Drinking Water Directive (DWD), which focuses on the end-product (delivered drinking water) and the protection of human health (EC, 2020). The broader environmental framework is provided by the Water Framework Directive (WFD), which sets objectives for the status of Europe's surface waters and groundwater, regardless of whether they are used for drinking water (EC, 2000). For groundwater specifically, the WFD is complemented by the Groundwater Directive (GWD), which defines key criteria and standards for assessing and preventing groundwater pollution (Directive 2006/118/EC, 2006).

#### **The Drinking Water Directive**

The Drinking Water Directive (DWD) was originally adopted in 1998 to protect human health from the adverse effects of contamination of water intended for human consumption by setting common minimum requirements for drinking water quality across the European Union. In 2020, the directive was recast as Directive (EU) 2020/2184, which entered into force on 12 January 2021. The revised directive retains the same overall objective but strengthens the preventive logic of the framework by introducing a more explicit risk-based approach to drinking water safety across the supply chain, including risk assessment and risk management of catchment areas for abstraction points. Member States were required to transpose the directive into national law by 12 January 2023. In Sweden, this was reflected, among other things, in new national drinking water regulations issued by the National Food Agency, which entered into force on 1 January 2023, although some provisions began to apply only from 1 January 2026.

Compared with the earlier directive, the recast DWD also updates and expands the list of monitored parameters and introduces new mechanisms for dealing with substances of emerging concern. This includes a watch-list system at EU level and new provisions addressing pollutants of concern such as endocrine-disrupting compounds and microplastics. Of particular relevance is the introduction of the parameters PFAS Total and Sum of PFAS, with harmonised EU limit values that became mandatory for Member States from 12 January 2026. Together, these changes illustrate how the revised directive combines traditional drinking water quality regulation with a stronger preventive and forward-looking approach.

#### **The Water Framework Directive**

While the Drinking Water Directive focuses on protecting human health, aquatic ecosystems also depend on water quality. The WFD provides the overall framework for protecting and improving Europe's waters by preventing deterioration and aiming for "good status" (with different definitions for surface water and groundwater).

The WFD is also directly relevant for drinking water abstraction because it requires Member States to identify waters used for the abstraction of drinking water and to

ensure the necessary protection, including the establishment of safeguard zones where appropriate.

### **The Groundwater Directive**

The Groundwater Directive (2006/118/EC) is a daughter directive under the WFD that specifies how groundwater chemical status should be assessed and protected. It includes EU-wide groundwater quality standards for nitrates (50 mg/L) and pesticides (0.1 µg/L per substance, 0.5 µg/L total) and requires Member States to set threshold values for other pollutants, monitor groundwater, and identify and reverse significant upward pollution trends.

### **4.3.3 Area Protection in Chapter 7 of the Swedish Environmental Code (Miljöbalken, 1998:808)**

Chapter 7 of the Environmental Code was introduced as part of the 1998 Environmental Code reform, which entered into force on 1 January 1999 (Government of Sweden, 1998). The reform aimed to consolidate previously fragmented environmental legislation into a more coherent legal framework oriented towards sustainable development. In general, the area-protection provisions in Chapter 7 replaced and systematised rules that had previously been spread across older legislation. For water protection areas specifically, the immediate predecessor was the Water Act (*Vattenlagen*, 1983:291), under which protection of water abstraction sources was already regulated before being incorporated into the Environmental Code.

Today, Chapter 7, *Skydd av områden*, provides the main legal basis for area protection in Sweden and is the key chapter for the establishment of water protection areas. For WPAs, Sections 21 and 22 are particularly important. Under Chapter 7, Section 21, a County Administrative Board or a municipality may designate a land or water area as a water protection area in order to protect a groundwater or surface water resource that is used, or can be expected to be used, for water abstraction. Chapter 7, Section 22 further states that the authority establishing the WPA must adopt the protection regulations needed to fulfil its purpose. The decision may also include practical requirements such as signage or fencing, including the use of another party's land if necessary. The regulations apply immediately even if the decision is appealed, and exemptions may be granted where special reasons exist.

The Environmental Code is supplemented by Ordinance (1998:1252) on area protection under the Environmental Code, which provides procedural and administrative rules relevant to WPA implementation. The ordinance assigns the Swedish Agency for Marine and Water Management (SwAM) central responsibility and guidance functions for water protection areas. It also requires that affected landowners and holders of special rights be given the opportunity to comment before a decision is made, normally with a minimum response period of one month. In addition, municipalities and County Administrative Boards must consult each other, and relevant sector authorities,

including SGU in groundwater-related matters, must be consulted where appropriate. Decisions must generally be publicly announced, and the ordinance also provides for mapping, documentation, and registration of protected areas. Together, these provisions define both the legal content of WPA decisions and the main procedural safeguards surrounding their establishment.

### **4.3.4 The Swedish Handbook on Source Water Protection**

The main national reference for how water protection areas are prepared in practice is the guidance published by the Swedish Agency for Marine and Water Management (SwAM), here referred to as the Swedish handbook on source water protection areas (SwAM, 2021). The legal basis for designating water protection areas and adopting protection regulations is described in Section 3.2.3.

In 2021, SwAM published new guidance on the establishment and management of water protection areas (Swedish title: *Vägledning om inrättande och förvaltning av vattenskyddsområden*) (SwAM, 2021). This guidance replaced the earlier handbook published by the Swedish Environmental Protection Agency (Naturvårdsverket or SEPA) (SEPA, 2011). The SwAM guidance describes roles and responsibilities of the actors involved in the water protection process, recommends what an application should contain, and provides advice on how the decision-making authority can handle the case.

A key shift in the 2021 guidance is the explicit emphasis on risk assessment as the organising logic for source water protection work. SwAM recommends a systematic workflow where risks are identified, analysed, and evaluated, and where the conclusions from that risk assessment motivate both the delineation (and any zone division) and the proposed protection regulations. In practice, this means that delineation and restrictions should be argued from the local risk picture and vulnerability, rather than primarily from pre-defined time criteria.

The guidance should also be understood in relation to the older national “package” of advice. The earlier approach was closely tied to SEPA’s handbook and the general advice on water protection areas (NFS 2003:16). That general advice has since been repealed, and current national guidance is instead provided through SwAM’s guidance material.

Finally, it is important to stress that the SwAM handbook is guidance rather than a legal instrument in itself. It does not create legal obligations in the same way as the Environmental Code or an individual protection area decision. However, it strongly shapes expectations in practice, since applications and proposed regulations are assessed against established national guidance during review and decision-making.

## 4.4 Institutional Context

This section describes how Sweden's administrative structure and planning responsibilities shape the implementation of water protection measures. It clarifies which authorities are responsible at different levels, and the legal basis for their roles.

### 4.4.1 Spatial Planning in Sweden

To understand the Swedish spatial planning system, it is useful to start with the country's administrative structure. Sweden is a constitutional monarchy with a strongly decentralised public administration.

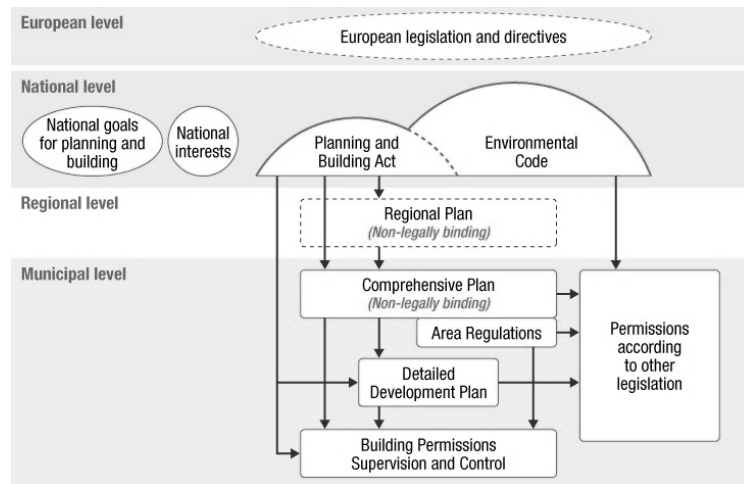
At the national level, ministries are relatively small and rely on topic-specific agencies for implementation and technical support. Up to the end of 2022, the main responsibility for spatial planning at national level was with the Ministry of Environment (Larsson, 2006). The Ministry of Environment was dissolved by December 2022, and its responsibilities were transferred to the Ministry of Climate and Enterprise. Table 2 summarises the main authorities and responsibilities across administrative levels, and Figure 4 illustrates the Swedish planning system.

**Table 2.** Sweden's administrative structure for spatial planning from the national to the regional level. The authorities are listed for each level and their corresponding responsibilities.

	<b>Responsible Authority</b>	<b>Responsibilities</b>
<b>National level</b>	Ministry of Climate and Enterprise, Ministry of Finance, Ministry of Infrastructure (supported by Boverket <sup>1</sup> , Naturvårdsverket <sup>2</sup> , Trafikverket <sup>3</sup> )	<ul style="list-style-type: none"> <li>- Legal proposals</li> <li>- Define directions concerning planning</li> </ul>
<b>Regional level</b>	State county administration and an elected county council	<ul style="list-style-type: none"> <li>- Public health services</li> <li>- Promote county development</li> <li>- Recommend, instruct, and control municipalities</li> </ul>
<b>Local level</b>	Municipal council	<ul style="list-style-type: none"> <li>- Responsible for most spatial planning</li> <li>- Further responsibilities regarding infrastructure such as water and sewage work, sanitary, energy planning, parks etc.</li> </ul>

<sup>1</sup>Boverket = National Board of Housing, Building and Planning, <sup>2</sup>Naturvårdsverket = Swedish Environmental Protection Agency, <sup>3</sup>Trafikverket = National Road Administration

At the regional level, Sweden is divided into 21 counties, each governed by a county administration and a county council. The counties have substantial autonomy, and the national government cannot interfere in individual case decisions. In spatial planning, a regional plan may be adopted when coordination across municipalities is needed or when there is a need to set a shared development direction. Regional plans are not legally binding for municipalities, but they provide decision support and guidance.



**Figure 4.** The Swedish Planning System (MLIT, 2014)

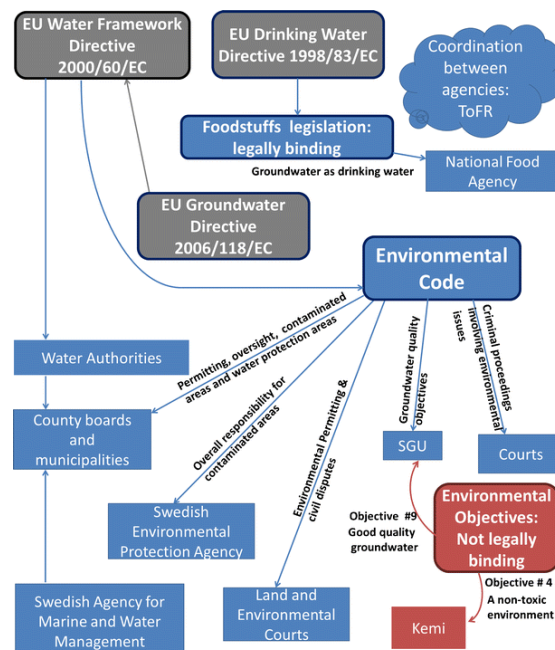
The local level consists of 290 municipalities, each governed by an elected municipal council. Municipalities manage most spatial planning in Sweden, as stipulated in the Planning and Building Act 2010:900 (Larsson, 2006; Swedish National Board of Housing Building and Planning, 2018), which is the central act for spatial planning. This strong municipal role is often described as the “municipal planning monopoly”. Each municipality develops a comprehensive plan, which is reviewed and revised every five years, to indicate how land and resources should be used and to ensure that national interests are considered at the municipal level. Where major changes or expansions are planned, a detailed plan may be prepared for a specific area. In general, plans at different administrative levels function as decision-support tools rather than legally binding instruments (Larsson, 2006). An important exception is the detailed plan, which becomes legally binding once adopted, whereas the comprehensive plan is not.

#### 4.4.2 Spatial Planning for Protected Areas in Sweden

Sweden’s modern system for protected areas and environmental regulation emerged in response to industrialisation and growing public health concerns. With increasing problems related to drinking water supply and wastewater treatment in the late 1800s, the Health Protection Act was enacted in 1874 (Naturvårdsverket, 2017). This legislation regulated natural resource extraction, aimed to protect people from environmentally hazardous activities, and introduced land-use regulation for different purposes.

In 1909, Sweden became the first country in Europe to establish nine national parks and enacted the Nature Protection Act (Naturvårdsverket, 2017). This represented a shift towards protecting nature itself through legislation. The first legislation specifically addressing natural water sources was the Water Act of 1918. The act regulated the use of water resources but primarily enabled exploitation, mainly for hydropower. A revision in 1983 aimed at stronger environmental protection but did not fundamentally change the focus on exploitation.

Today, Sweden has a complex planning and governance structure for implementing water protection measures (see Figure 5). At European level, the Water Framework Directive (WFD) and the Drinking Water Directive (DWD) provide key drivers for water protection. The WFD informs the Swedish Environmental Code. In Sweden, drinking water is regulated as food and is therefore under the control of the National Food Agency (Livsmedelverket), which is informed by the DWD. County boards and municipalities are the main authorities responsible for granting permits and overseeing water protection measures. Their work is informed by the water authorities and the Swedish Agency for Marine and Water Management (SwAM). Several other agencies support protection from contamination (for example, the Swedish Environmental Protection Agency) and develop maximum limit values for contaminants (for example, the Swedish Geological Survey and the Swedish Chemicals Agency). These limit values are in turn guided by European Directives and the Swedish Environmental Objectives. Finally, the Land and Environmental Courts grant environmental permits for activities that may contaminate water resources, while criminal courts handle criminal charges related to source waters.



**Figure 5.** Swedish groundwater policy according to national law. Blue marked boxes indicate legally binding Swedish law, grey represent legally binding European law, and red is not legally binding. Note that the reference is from 2013 and is an example illustrating the complexity of the Swedish spatial planning system regarding water sources (from Lewis et al., 2013).

## **4.5 The Practice of Water Protection Area Implementation**

### **4.5.1 What is a Water Protection Area**

A water protection area is a geographically defined area where land use and activities are regulated to reduce risks to a drinking-water source. The idea is to focus protection on the parts of the landscape that contribute water to an abstraction point or water body, and to translate that into zones with specific requirements and restrictions. Water protection areas appear under different names, including drinking-water protected areas, safeguard zones, and water protection zones. Although terminology and legal design vary between countries, the core principle is the same: protection is implemented through delineated zones intended to prevent contamination and safeguard supply reliability.

The main goal of a water protection area is to protect the drinking-water source by reducing the likelihood of harmful events and limiting their potential consequences. In practice, water protection areas are one instrument within a broader toolbox of water protection measures. Importantly, protection measures can also be implemented without formally establishing a water protection area, for example through voluntary agreements, targeted monitoring, operational controls, or general land-use regulation. Establishing a water protection area represents a formalisation of source protection, where restrictions and requirements are specified, geographically referenced, and made enforceable. This formal step can strengthen clarity and consistency in how protection is applied, and it provides a durable basis for managing land-use conflicts and documenting the rationale for restrictions over time.

Water protection areas are commonly framed as part of a multiple-barrier approach to drinking-water safety. In the WHO “source to tap” perspective, safety is achieved through several barriers that together reduce risk, including source protection, treatment, secure distribution, monitoring and testing, and competent operation and training. Within this framework, source water protection is often described as the first barrier, because preventing contamination at the source reduces the need for corrective action later in the system and increases overall robustness.

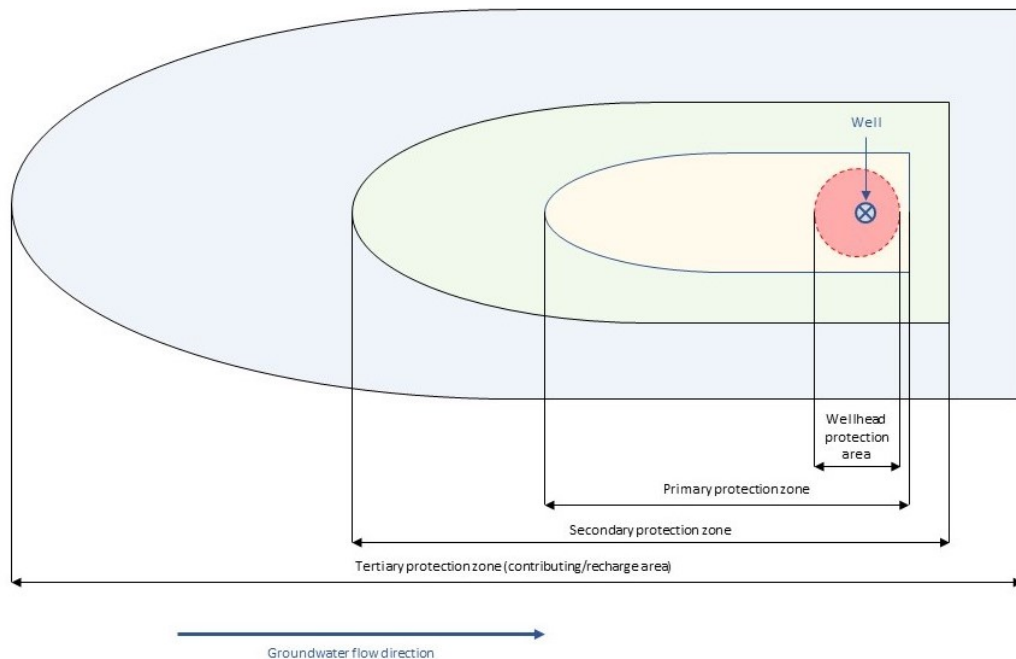
### **4.5.2 Wellhead Protection Areas as a Specific Type of WPA**

For groundwater supplies, a common and well-established form of water protection area is the wellhead protection area (WHPA). WHPAs were originally developed primarily to protect abstraction wells from microbial and chemical contamination. Their zoning is typically based on advective travel-time considerations (Enzenhoefer et al., 2014), that is, on how long it takes for groundwater (and dissolved contaminants) to move from a point in the aquifer to the abstraction point. Travel-time based zones are intended to support practical protection in two ways: they provide a time window for response in case of incidents such as spills, and they reflect that some contaminants may attenuate or decline to acceptable levels over time before reaching the well (Chin and Asce, 2018). To translate this into management, WHPAs are commonly subdivided into zones with

tiered protection levels, where restrictions are typically strongest closest to the abstraction point and decrease with distance.

A generic zoning scheme distinguishes a wellhead (or abstraction) zone closest to the well, followed by primary, secondary, and sometimes tertiary zones (see Figure 6). The wellhead zone is the immediate area around the well and is often physically protected (for example by fencing) with very strict limitations on activities. The primary protection zone is commonly defined by a short travel time to the well and is intended to protect against acute contamination risks. The secondary zone extends the travel-time criterion to a longer period, allowing more time for response and, depending on context, permitting a wider range of land uses than in the primary zone. A tertiary zone, where applied, typically corresponds to the remaining contributing recharge area.

A range of delineation methods exists, spanning simple screening approaches to site-specific modelling. The US-EPA (1987) classifies WHPA delineation methods from low-complexity fixed-radius approaches to more data- and resource-intensive numerical models. The methods listed in Table 3 reflect this spectrum, including calculated fixed-radius methods based on a time-of-travel criterion, simplified variable-shape approaches based on idealised flow assumptions, analytical methods, hydrogeologic mapping, and numerical flow and transport modelling.



**Figure 6.** Theoretical wellhead protection zones.

**Table 3.** Delineation methods for groundwater sources

<b>Method</b>	<b>Description</b>
<b>Fix radius method (arbitrary fixed radius)</b>	<ul style="list-style-type: none"> <li>– Protection area is a circle around the well</li> <li>– Discharge rate is often the only considered parameter when choosing the distance</li> </ul>
<b>Fix radius method (calculated fixed radius)</b>	<ul style="list-style-type: none"> <li>– Protection area is a circle around the well</li> <li>– Circle's radius is calculated based on specific time-of-travel criteria (critical time for a contaminant to reach the well)</li> </ul>
<b>Simplified variable shapes</b>	<ul style="list-style-type: none"> <li>– A set of various standardized forms are generated beforehand by experts using uniform flow equations</li> <li>– Non-experts use the most suitable shape based on the site-specific hydrogeology and the pumping rate, place it upon the well, and rotate it dependent on the groundwater flow</li> <li>– The shape represents the delineation of the water protection area</li> </ul>
<b>Analytical methods</b>	<ul style="list-style-type: none"> <li>– Equations describe the groundwater flow and contaminant transport for specific conditions</li> <li>– Main steps are to identify the distance to the downgradient and the distance to the upgradient</li> </ul>
<b>Hydrogeologic mapping methods</b>	<ul style="list-style-type: none"> <li>– Experts identify the flow boundaries with the aid of maps</li> <li>– The geological boundaries correspond to the water protection area</li> </ul>
<b>Numerical flow/transport models</b>	<ul style="list-style-type: none"> <li>– Use of software (computer models) to solve the groundwater flow equations and particle transport equations numerically</li> </ul>

In Sweden, the guidance document used until 2021 (SEPA, 2011) describes a comparable tiered zoning approach for groundwater sources. The catchment is divided into an abstraction zone and three protection zones. Zone I is defined by a 100-day travel time, Zone II by a one-year travel time, and Zone III by the remaining recharge area (SEPA, 2011). Table 4 summarises this example of how WHPA zoning has been defined in Swedish practice.

**Table 4.** Example showing how wellhead protection zoning can be defined in Sweden based on time of travel criteria.

<b>Wellhead Protection Area Boundaries</b>				
<b>Abstraction Zone</b>	<b>Zone I</b>	<b>Zone II</b>	<b>Zone III</b>	<b>Reference</b>
Not specified	100 days TOT	365 days TOT	Recharge Area	(SEPA, 2011)

Recent guidance increasingly emphasises a risk-based approach rather than relying on travel-time criteria alone. This does not make travel-time concepts obsolete. Instead, travel time remains one relevant line of evidence for characterising vulnerability and for understanding how quickly hazards in different parts of the catchment could affect the

abstraction point. In a risk-based framework, travel-time analysis can therefore inform, rather than dictate, zoning decisions and the selection of protection measures.

### 4.5.3 Steps in Establishing a Water Protection Area

Establishing a Swedish water protection area (WPA) is governed by Chapter 7 of the Environmental Code (Miljöbalken) and the procedural requirements in Ordinance (1998:1252) on area protection. The legislation defines what a WPA decision must contain and who must be consulted, but it does not prescribe a single standardised workflow inside organisations. The exact sequence and decision path varies mainly with whether the County Board Administration or the municipality is the formal decision-maker.

**Table 5.** Main steps in the establishment and management of a Swedish water protection area, showing the typical actors involved and their formal roles based on the allocation of responsibilities in the regulatory framework.

Step	Description	Main actor(s)	Role(s)
<b>1. Need for a new or updated WPA identified</b>	A need for stronger protection of a drinking water resource is identified, because the existing protection is missing, outdated, or no longer considered sufficient.	Water utility/drinking water producer; municipality	Initiator; often future applicant
<b>2. Application prepared</b>	The material needed to establish the WPA is prepared. This includes the proposed boundary, proposed protection regulations, and the supporting investigations needed to justify them.	Water utility/drinking water producer; municipality	Applicant
<b>3. Application submitted</b>	The applicant submits the WPA application to the competent authority.	Water utility/drinking water producer; municipality	Applicant
<b>4. Application received and case handled</b>	The competent authority receives the application, checks that it has sufficient content and scope, and handles the case independently.	Municipality or County Board Administration	Decision-making authority
<b>5. Expert authorities are consulted</b>	Relevant expert authorities provide knowledge and guidance before the final decision is taken. SGU contributes groundwater-related expertise.	SGU; decision-making authority	Expert authority; decision-making authority

Step	Description	Main actor(s)	Role(s)
<b>6. Decision on WPA and regulations</b>	A formal decision is taken on whether to establish the WPA, including its delineation and the protection regulations that apply within it.	Municipality or County Board Administration	Decision-making authority
<b>7. Compensation issues handled where relevant</b>	If the regulations lead to compensable restrictions on land use, compensation is handled in connection with the decision.	Water Utility (responsible body for the water supply)	Compensation party
<b>8. Permits and exemptions under the regulations</b>	After the WPA has been established, applications for permits or exemptions under the protection regulations are examined.	Municipality or County Board Administration	Permitting authority
<b>9. Compliance is monitored</b>	Compliance with the WPA regulations, and with conditions attached to special permits, is monitored.	Municipality or County Board Administration	Supervisory authority
<b>10. National guidance and information support</b>	National authorities provide guidance, maintain registers, and support the system with technical, legal, and groundwater-related knowledge.	Swedish Agency for Marine and Water Management; Swedish Environmental Protection Agency; SGU; Water Authorities	Central guidance authority; register authority; expert authority; water management authority

The process usually starts when a municipality or water utility identifies a need for a new or updated WPA, for example because protection is missing, outdated, or no longer considered sufficient. The applicant then prepares the application, including the proposed boundary, draft protection regulations, and the supporting investigations needed to justify them. The application is submitted to the competent authority, which is either the municipality or the County Administrative Board, depending on the case. That authority receives the application, checks that it has sufficient content and scope, and handles the case as the formal decision-making authority. During this stage, relevant expert authorities are consulted, in particular SGU for groundwater-related expertise.

After the review and consultation stage, the competent authority decides whether to establish the WPA and adopt the associated regulations. Where the decision results in compensable restrictions on land use, compensation issues are handled in connection with the decision, typically by the municipality or water utility as the party in whose

interest the WPA is established. Once the WPA has been established, the process continues through implementation and management. This includes the examination of permits and exemptions under the regulations, monitoring of compliance, and support from national authorities that provide guidance, maintain registers, and contribute technical and legal expertise.

### **The Role of Consultants**

Although consultants are not assigned a formal statutory role in the legislation governing water protection areas, they are often central in practice, particularly during the preparation phase. Their core contribution is usually the production of the technical basis for the application, including hydrogeological assessment, risk analysis, delineation proposals, and supporting documentation. In many cases, however, their role extends beyond the technical assessment. Consultants may also support municipalities in drafting the wording of protection regulations and related documents, assist in communication with stakeholders and affected parties, and provide post-decision support, for example in relation to implementation, interpretation of the regulations, and follow-up or monitoring activities. The municipality, water utility, or other competent authority nevertheless retains the formal responsibility for coordination, statutory consultation, handling of comments, and preparation of the case for decision-making.

Within this broader supporting role, the technical assessment typically follows a recurring workflow (see Table 6). The work usually begins with a start-up dialogue with the client to clarify the purpose, scope, expected decision pathway, and deliverables. This is followed by the compilation of existing data, desk studies, review of raw-water monitoring data, and a site visit to understand local conditions and support the risk inventory. On this basis, the consultant develops or refines a conceptual hydrogeological model, which is then used to assess flow conditions, travel times, capture zones, and intrinsic vulnerability. Potential contamination sources and activities are subsequently inventoried and assessed in relation to vulnerability and transport conditions, providing the basis for delineation of the proposed water protection area and its internal zones. Draft protection regulations are often developed in parallel so that the proposed restrictions correspond to the identified risks and pathways. The results are typically compiled in a technical supporting report and revised through several rounds of dialogue and comments before the proposal is finalised for submission and decision.

**Table 6.** Typical consultant tasks in the preparation of a Swedish water protection area application.

<b>Phase of consultant work</b>	<b>Tasks</b>	<b>Output</b>
<b>1. Start-up and scoping</b>	Clarify purpose, scope, decision pathway, abstraction conditions, and expected deliverables together with the client	Agreed scope and work plan
<b>2. Data compilation and desk study</b>	Compile previous reports, maps, well and aquifer data, land use, contamination history, and monitoring data	Technical data basis
<b>3. Site visit and risk inventory preparation</b>	Visit the site, review local conditions, identify relevant sources, pathways, and areas for further assessment	Site understanding and basis for risk inventory
<b>4. Hydrogeological assessment</b>	Develop or refine the conceptual hydrogeological model, including aquifer properties, recharge, protective layers, and key parameters	Conceptual model and hydrogeological interpretation
<b>5. Flow and travel-time assessment</b>	Estimate groundwater flow directions, travel times, capture zones, and areas of influence under pumping	Basis for delineation and zoning
<b>6. Vulnerability assessment</b>	Assess intrinsic vulnerability based on hydrogeological conditions, protective layers, permeability, recharge, and inferred transport conditions	Vulnerability classification
<b>7. Risk inventory and analysis</b>	Inventory contamination sources and activities and assess their significance in relation to vulnerability and transport	Risk inventory and risk assessment
<b>8. Delineation and drafting</b>	Propose the WPA boundary, internal zones, and draft protection regulations aligned with the identified risks	Delineation proposal and draft regulations
<b>9. Technical documentation</b>	Compile the technical supporting report, maps, assumptions, methods, and rationale	Technical supporting documentation
<b>10. Revision and iteration</b>	Revise the proposal through dialogue with the client and after comments from authorities and affected parties	Finalised technical basis for submission

## 4.6 Identified Needs from the Environment

The preceding sections show that the challenges of groundwater protection in Sweden arise at several different points in the WPA process. A first challenge concerns the technical basis for delineation and zoning. Groundwater protection in Sweden takes place in heterogeneous hydrogeological settings. At the same time, many small- and medium-sized supplies have limited data, time, and technical resources. This creates a difficult balance. Delineation and zoning still need to be credible and defensible in planning and decision-making, but highly advanced numerical models are often too demanding in practice. What is needed are methods that can handle uncertainty and hydrogeological complexity without becoming unrealistic to apply.

A second challenge concerns the increasing emphasis on risk-based protection. WHO Water Safety Plans, the revised Drinking Water Directive, and recent Swedish guidance all stress the importance of assessing hazards, vulnerability, and consequences in a more systematic way. In practice, however, risks may still be insufficiently structured or difficult to communicate, especially when they must be linked to spatial protection measures and regulations. There is therefore a need for approaches that support risk-based assessments in a transparent and understandable way.

The environment chapter also shows that WPA implementation is not only a technical and legal exercise. Many actors are involved, including municipalities, County Administrative Boards, water utilities, consultants, landowners, and other affected stakeholders. In such a setting, technical defensibility alone is often not enough. Protection measures must also be understandable and justifiable in relation to competing land uses and interests. A recurring challenge is that the benefits of protection are often less visible than the immediate restrictions, costs, and possible compensation claims. This makes it important to find ways of identifying and communicating both the benefits and the costs of protection more clearly.

Another challenge is that WPA work is procedurally complex. It involves applications, technical supporting reports, consultation, review, decisions, permits, and follow-up. In practice, much of this work depends on repeated compilation of data, site screening, interpretation, documentation, and iteration between actors. This means that implementation may be slowed not only by scientific complexity, but also by fragmented workflows and high transaction costs. More practical, reproducible, and transparent ways of working are therefore important if such processes are to be manageable in routine practice.

Finally, the Swedish drinking-water landscape is not uniform. It includes private wells, community-managed supplies, and municipal systems, and these different forms of supply may be associated with different levels of protection, service quality, and exposure to risk. Because water protection and spatial planning may affect different groups in different ways, it is also important to understand whether the burdens and benefits of protection are distributed unevenly.



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## 5 DSR FRAMEWORK – KNOWLEDGE BASE

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*In the DSR framework, the knowledge base provides the concepts, theories, methods, and analytical approaches that can be used to address the needs identified in the environment. In this thesis, the need for such a knowledge base arises from the practical challenges described in Section 4.6. These challenges indicate that improving drinking water protection is not only a matter of better hydrogeological analysis, but also of better ways to assess, justify, communicate, and evaluate protection measures.*

### 5.1 Method Selection

The selection of methods in this thesis was guided by the practical needs identified in the environmental context and by the role of the knowledge base within the DSR framework. Several potentially relevant methods exist for improving water protection, but they address different bottlenecks in practice and are not equally suitable for adaptation into practitioner-oriented approaches. Some methods are already closely associated with source-water protection, such as risk assessment and groundwater modelling. Others reflect broader developments in water management and policy, including ecosystem services, cost-benefit analysis, and environmental justice. The aim was therefore not to identify the theoretically best method in isolation, but to select forms of knowledge that could help address the key implementation challenges identified in this thesis.

A consistent selection criterion was practical applicability. Each method was considered in terms of whether it could be translated into an approach that practitioners could realistically use, particularly in the context of small and medium-sized supplies in Sweden. The resulting set of methods reflects the fact that implementation challenges arise at different points in the protection process. The technical basis may be uncertain, for example in delineation or conceptual understanding of the groundwater system. Risks may be insufficiently structured or difficult to communicate. The benefits of protection may remain poorly articulated compared with the more visible costs and restrictions. For this reason, the thesis combines methods that strengthen different parts of the workflow: the Analytic Element Method to improve the technical basis for delineation, risk management to structure hazards and prioritisation, ecosystem service

assessment to identify and communicate benefits, cost-benefit analysis to support economic justification, and environmental justice to examine distributional aspects of drinking water protection and provision. Together, these methods form the knowledge base used to develop the artifacts presented later in the thesis.

## 5.2 The Analytic Element Method

A key step in developing a water protection area is delineating the contributing area (capture zone) to the abstraction point. For groundwater sources, delineation is often uncertain because subsurface properties are only partly known and may vary substantially across space. In practice, this creates a familiar trade-off. Simple screening calculations can be too coarse to represent boundaries, while fully discretised numerical models can be data- and time-intensive to build and calibrate, which is a challenge for many small and medium-sized supplies.

The analytic element method (AEM) offers a useful middle ground. Pioneered by Strack, AEM is a groundwater modeling technique that simulates groundwater flow by superimposing elementary analytical solutions, such as line sources or sinks, to represent complex aquifer configurations in two or three dimensions (Haitjema, 1995; Strack, 1999, 1989). Instead of discretising the full model domain into a grid, the model is defined by these elements and their boundaries, while hydraulic head and discharge can be evaluated continuously at any point in the domain. This makes AEM efficient for steady-state regional and catchment-scale problems where the goal is to understand flow patterns and delineate capture zones without building a full gridded model.

AEM has also been used in practical wellhead and source protection work for decades, and several software options exist for delineating protection areas with AEM. A widely used example is the U.S. Environmental Protection Agency's Wellhead Analytic Element Model (WhAEM), which was developed to support capture zone delineation and protection area mapping in wellhead protection and source water assessment planning and includes a user-oriented workflow. However, tools like WhAEM are primarily deterministic in the sense that they produce a single delineation for a chosen parameter set. They do not provide a built-in, easy-to-use way to propagate parameter uncertainty into the delineation result, and WhAEM is typically distributed as closed software, which limits transparency and customisation for method development.

This gap is one reason why open and scriptable AEM implementations are attractive in a research-to-practice context. In recent years, Bakker and Kelson developed open-source AEM packages in Python, which are designed to be flexible and can compute head, flow, and leakage in layered systems (Bakker and Kelson, 2009). But the key point for this thesis is that a Python-based, open-source codebase makes it feasible to extend the modelling workflow and modify it for the demands of practitioners.

## 5.3 Ecosystem Services Assessments

Drinking water sources are complex systems that generate a wide range of benefits for society. Capturing this breadth in a consistent way is often challenging, particularly when

comparing sites or evaluating alternative water protection measures (WPM). Ecosystem service assessments can help address this challenge by providing a structured approach to identifying and describing benefits, thereby supporting a more comprehensive evaluation of WPM.

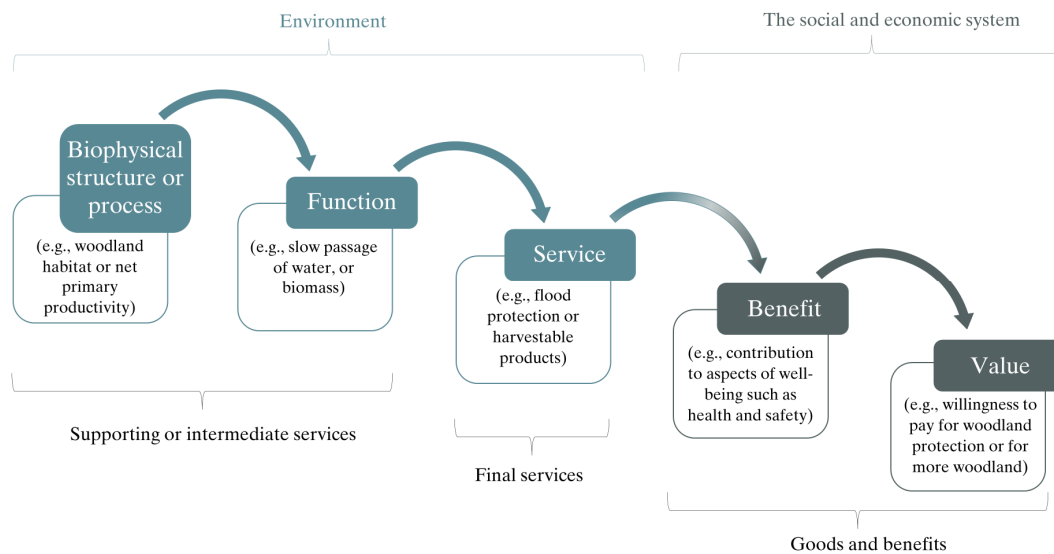
### **5.3.1 Ecosystem Services**

Throughout history, people have relied on nature and on well-functioning ecosystems. The ecosystem services (ES) concept provides a framework for describing this dependence in terms of benefits that ecosystems provide to people. Ecosystem services are often defined as “the benefits people obtain from ecosystems” (Costanza et al., 1997). Early work linked ecosystem functioning to human welfare, with Westman (1977) formalising this relationship. The concept was later further developed and brought into broader use through foundational contributions such as Daily (1997), Costanza et al. (1997), and the Millennium Ecosystem Assessment (MA, 2005). Since then, ecosystem services have increasingly been used as a way to organise information about how changes in ecosystems can affect society.

To support systematic assessment, several classification systems have been developed. Commonly used examples include the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018), the Economics of Ecosystems and Biodiversity (TEEB) (TEEB, 2010) and the Millennium Ecosystem Assessment (MA) (MA, 2005)). These frameworks share the overall aim of making ecosystem services assessments more consistent and comprehensive, while differing in structure and intended applications. CICES is a standardised classification scheme and is broadly accepted, recognised, and applied in ecosystem services research in Europe (Anzaldua et al., 2018; Kaval, 2019). It builds on earlier classification schemes such as TEEB and MA and is commonly linked to the cascade model as a conceptual framing (de Groot et al., 2010).

The cascade model describes a chain that connects the natural system to outcomes in the social and economic system (see Figure 7). In this conceptualisation, biophysical structures and processes in the natural system underpin ecosystem functions. These functions generate ecosystem services, which represent contributions that ecosystems can provide to people. When services are used, accessed, or otherwise realised in the social and economic system, they result in benefits. These benefits can then be described and, where relevant and feasible, valued. This framing is useful in assessments because it clarifies that the same biophysical conditions do not automatically translate into the same societal outcomes. The link between ecological conditions and human well-being depends on how services are realised and by whom.

CICES operationalises ecosystem services assessment through a hierarchical structure that resembles a taxonomic approach used for categorising organisms. At the highest level, services are divided into sections (provisioning, regulating, and cultural services). These are further divided into divisions, groups, and classes. In addition, examples are provided for classes to guide interpretation and help users identify relevant services in practice. This hierarchical structure can support consistency in how services are described and compared, while still allowing assessments to be tailored to specific contexts and decision needs.



**Figure 7.** The CICES cascade model (modified after (Haines-Young and Potschin, 2018)).

### 5.3.2 Ecosystem Services as a Planning Method in Water Protection

A central challenge in the implementation of water protection measures is that costs and restrictions are often immediate and visible, while the benefits largely take the form of avoided impacts that are harder to document and communicate. This asymmetry can make it difficult to justify protection measures and to compare alternatives in a transparent way. Ecosystem service assessment offers a structured approach to describing these otherwise less visible benefits, including avoided damages, and it has increasingly been used in planning contexts where trade-offs must be negotiated (von Haaren et al., 2016).

In the context of water protection, ecosystem services can help translate hydrological and ecological functions into categories that are meaningful for decision-making and communication. The concept has been argued to increase awareness of complex ecosystem interactions and to provide a shared language for expressing the values that people attribute to landscapes (Fürst et al., 2014). This matters for WPA processes

because protection measures are spatially defined, affect multiple land users, and require legitimacy beyond technical defensibility.

Modern planning approaches emphasise the role of the local community, with values negotiated through participatory processes. Opdam (2016) argues that ecosystem service valuation should be understood primarily as a social activity rather than an economic one. For water protection, this perspective is relevant because the acceptability of restrictions often depends on whether stakeholders recognise the protected benefits as real and shared. Creating inventories of ecosystem services used by different stakeholder groups can support this process by making dependencies and co-benefits explicit and by revealing potential common ground among actors affected by protection measures (von Haaren et al., 2016).

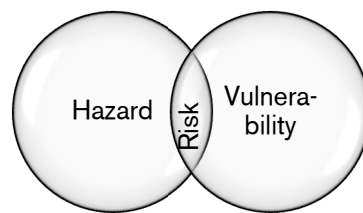
Overall, integrating ecosystem services into water protection work can strengthen the basis for justifying protection measures, improve communication of public goals, and support negotiations about trade-offs and compensation by making benefits more explicit and comparable (von Haaren et al., 2016).

## **5.4 Risk and Risk Management**

In industrial nations, risk has become the most prominent organizing concept that drives environmental legislation (Jasanoff, 1999). In drinking water protection, risk cannot be eliminated entirely, and risk assessments are therefore used to structure and prioritise remaining threats in a transparent way. To apply risk assessment meaningfully in source-water protection, the underlying concepts must first be defined. Risk depends on the presence of a hazard, the vulnerability of the source to that hazard, and the severity of consequences if an adverse event occurs, all under conditions of uncertainty. This section therefore introduces these concepts and follows the ISO 31000 risk management framing. Within source-water protection, this provides a practical structure for linking hazards and pathways to spatial protection measures and for documenting and communicating the basis for prioritisation.

### **5.4.1 Key Concepts in Risk Management**

Drinking water sources are exposed to pressures from natural processes and human activities. A pressure only constitutes a risk when two conditions are met: a stressor is present (a hazard), and the drinking-water source is vulnerable to the effects the hazard may cause. If either the hazard is absent or the source is not vulnerable, the pressure does not translate into a risk for the water source. Figure 8 illustrates this interplay. The concepts defined below provide the terminology used in this thesis to describe risks to drinking-water sources and to frame risk assessment.



**Figure 8.** Illustration of the interplay of hazard, vulnerability, and risk towards a drinking water source

**Hazard.** Rausand (2011) defines a hazard as a source of danger that may cause harm to an asset. For drinking-water sources, hazards can relate to source-water quality or to the availability of source-water quantity. Hazards concerning quality are a prerequisite for contamination events that may pose a danger to human health when water is used for consumption. Drinking-water hazards regarding quality can be grouped into chemical, microbial, physical, and radiological hazards (World Health Organization, 2019).

To connect hazards to practical risk assessment, it is useful to distinguish between a hazard source and a hazardous event. A hazard source may refer to an ongoing activity or a persistent circumstance (for example an agricultural practice or an industrial site). A hazardous event refers to the specific occurrence that results in an adverse effect on the water supply (for example a spill, leakage, or failure).

Chemical hazards can be naturally occurring, such as arsenic in groundwater, or originate from anthropogenic sources linked to industrial or agricultural activities. Microbial hazards consist of pathogens transmitted through drinking water, primarily of faecal origin (Ashbolt, 2004), including bacteria, viruses, and protozoa. Common pathogens include norovirus, rotavirus, *Giardia*, *Shigella*, *Helicobacter*, *Salmonella*, and *Cryptosporidium*. Ashbolt (2004) provides an overview of waterborne pathogens of concern, the diseases they cause, and their primary sources. Physical hazards affect the physical appearance or properties of water, including increased turbidity and suspended material such as sediment, metals, plastics, or stones (Tsitsifli and Kanakoudis, 2020). Radiological hazards may be naturally occurring, for example radon derived from the decay of uranium and thorium in rocks and soils, or anthropogenic, for example due to spills or leakages of radioactive materials at mines, landfills, or industrial sites.

**Vulnerability.** Hazards alone do not determine risk. Whether a hazard poses a risk depends on the vulnerability of the drinking-water source. In this thesis, vulnerability represents source and system characteristics that influence how readily water quality may be deteriorated or supply may be disrupted. Vulnerability is shaped by the existence and effectiveness of pathways and barriers between hazard sources and the abstraction point, as well as by attenuation processes along these pathways. A source can therefore be exposed to hazards in the catchment while still having relatively low vulnerability if protective layers, long travel times, or attenuation processes limit the connection between the hazard source and the receptor.

Machiwal et al. (2018) distinguish between intrinsic and specific vulnerability. Intrinsic vulnerability is determined by the physical characteristics of the system and is independent of contaminant type. Specific vulnerability describes vulnerability to a particular contaminant and therefore combines transport characteristics with contaminant properties and attenuation processes. This distinction is relevant in source-water protection because the same hydrogeological setting may be highly vulnerable to one hazard and less vulnerable to another, depending on transport and attenuation.

**Risk.** Even though the field of risk science is young (Aven, 2020), many definitions of risk exist. One of the most influential works in the risk field is Kaplan and Garrick's paper on the quantitative definition of risk (Kaplan and Garrick, 1981). In their formulation, risk is described through scenarios that may occur and cause harm to a system that is to be protected. For each event  $i$ , risk can be represented as a set of triplets consisting of the scenario description  $s_i$ , the probability  $p_i$  that the scenario occurs, and the consequence  $c_i$  if it occurs. Operationally, this framing requires the risk analysis to address three questions:

- i. What can go wrong?
- ii. How likely is it that that will happen?
- iii. If it does happen, what are the consequences?

Source-water protection aligns well with this framing because protection measures aim to reduce the likelihood and or consequences of adverse scenarios, while recognising that residual risk remains. Building on Kaplan and Garrick (1981), this thesis defines the risk ( $R$ ) posed by a hazard  $i$  to a drinking-water source as:

$$R_i = f(p_i, v_i, c_i) \tag{1}$$

where  $p$  is the probability of the hazard source causing a discharge of a hazardous substance or, in other ways posing a potential threat to the water source,  $v$  is the vulnerability of the water source concerning the hazard, and  $c$  is the consequence severity to the drinking water source due to the hazard.

**Uncertainty.** Uncertainty refers to a lack of complete certainty, meaning that more than one outcome is possible and the true outcome is not known (Hubbard, 2014). In risk assessment, uncertainty describes limitations in the information used to characterise hazards, vulnerability, probabilities, and consequences. It is therefore distinct from risk itself: risk describes adverse scenarios and their likelihood and consequences, whereas uncertainty describes the degree to which these quantities or categories are known.

In source-water protection, uncertainty occurs at multiple stages of the risk assessment. During hazard identification, uncertainty can relate to whether hazard sources and hazardous events have been comprehensively identified, and how they are represented. During vulnerability characterisation, uncertainty often concerns pathways, barriers, and attenuation processes that determine exposure. During risk analysis, uncertainty affects estimates or classifications of likelihood and consequence. These sources of

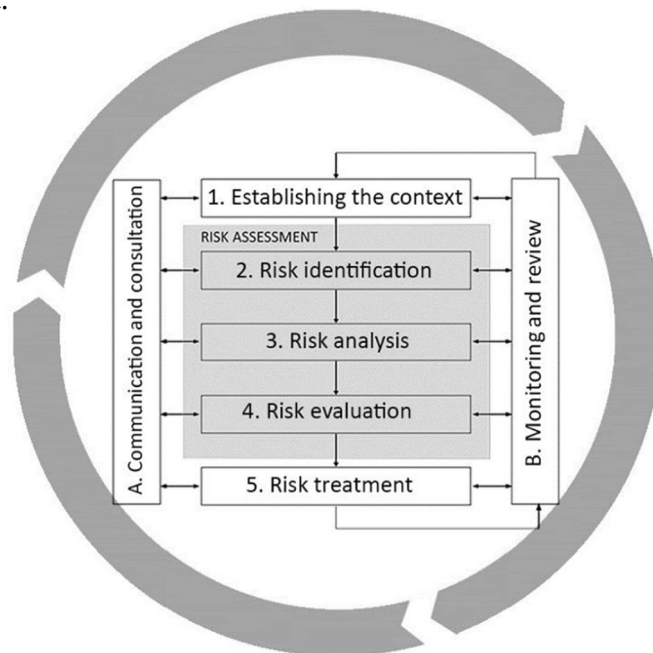
uncertainty can be carried forward explicitly when risks are compared across hazards or sites.

In this thesis, two types of uncertainty are distinguished. Parameter uncertainty refers to uncertainty in the numerical values of inputs used in assessments or models, such as hydrogeological properties, recharge, travel times, or other site-specific characteristics. Parameter uncertainty can be represented by specifying plausible ranges or probability distributions for parameters instead of single deterministic values (Hubbard, 2014). Model uncertainty refers to uncertainty in the model structure or conceptualisation used to represent the system, including whether relevant processes are included and whether dominant pathways are represented adequately.

Uncertainty is also commonly classified as aleatory or epistemic (Bedford and Cooke, 2002). Aleatory uncertainty arises from inherent variability and is not reduced by additional measurements. Epistemic uncertainty arises from lack of knowledge and can be reduced through improved information or understanding (Bedford and Cooke, 2002). Both components may contribute to parameter uncertainty and model uncertainty.

#### 5.4.2 Risk Management as a Standard Method

The International Organization for Standardization (ISO) defines risk management as *coordinated activities to direct and control an organization with regard to risk* (ISO, 2018). ISO 31000:2018 provides widely used guidance on risk management and describes a structured process for managing risks. Within this process, risk assessment is a central component and is commonly subdivided into risk identification, risk analysis, and risk. Figure 9 illustrates the overall risk management process and the position of risk assessment within it.



**Figure 9.** The risk management process based on ISO 31000:2018 (from (Laine et al., 2021))

Risk assessments are often categorised as qualitative, semi-quantitative, or quantitative. Qualitative risk assessments express risk using descriptive categories, for example high versus low risk, or colour-coded matrices (green–yellow–red) that group risks into classes. Quantitative risk assessments, in contrast, express risk using numerical values, typically through explicit estimates of likelihood and consequences. Semi-quantitative risk assessments represent an intermediate approach. Probabilities and consequences are first described using qualitative categories, but these categories are assigned numerical scores to allow calculations and facilitate comparisons. For example, the likelihood of an event may be expressed using categories such as “most unlikely” to “almost certain,” with corresponding scores (for example 1 to 5). Consequences may be described similarly, for example from “no consequences” to “catastrophic consequences,” again with assigned scores (for example 0 to 5). Combining likelihood and consequence scores results in a risk score for each hazard, which supports ranking and prioritisation more directly than purely qualitative results.

## 5.5 Cost-Benefit Analysis

Cost-benefit analysis (CBA) is a decision-support method developed to help public authorities compare competing projects and policies when costs are easy to observe in budgets, but benefits are partly non-market, and accrue over long time horizons. It provides a structured way to ask whether an intervention is socially worthwhile (meaning: *is society better off if we do this project, given that resources are scarce and could be used elsewhere?*), and to compare alternatives using a consistent accounting framework. Modern CBA is rooted in welfare economics and builds on early work on valuing public works through willingness-to-pay and consumer surplus, later becoming widely institutionalised in public investment appraisal (Talvitie, 2018).

Decisions in public policy and planning often involve trade-offs between competing objectives, impacts that occur at different times, and effects that are difficult to compare because they are expressed in different units. Cost-benefit analysis (CBA) is a method developed to address this challenge by providing a systematic framework to evaluate whether an intervention is economically justified and to compare alternative options on a consistent basis. In its simplest form, CBA asks whether the total benefits of an action outweigh its total costs, and by how much (Johansson and Kriström, 2018). By translating impacts into a common unit, applying a defined analytical perspective, and accounting for timing through discounting, CBA supports transparent comparison and prioritisation across alternatives.

CBA is an economic evaluation method used to assess policy measures, projects, or regulations by comparing their expected costs and benefits over time. The method is grounded in welfare economics and is typically carried out from a societal perspective, meaning that all relevant consequences for affected groups are considered, not only those reflected in market transactions (Johansson and Kriström, 2018). A standard CBA follows a repeatable sequence of steps.

A cost-benefit analysis begins by defining the problem and the boundaries of the assessment. This includes specifying the purpose of the intervention, identifying the relevant stakeholders, and deciding on the analytical perspective, for example whether the analysis is carried out from a societal, municipal, or sector-specific viewpoint. The chosen perspective determines which impacts are considered relevant and therefore sets the scope of the study.

The next step is to establish a baseline scenario and compare it with a set of realistic alternatives. The baseline represents the business-as-usual case against which the effects of possible interventions are judged. Each alternative must be described clearly enough that differences in impacts can be linked to specific measures, implementation choices, or levels of enforcement. Once the alternatives are defined, the relevant impacts of each option are identified relative to the baseline. These may include financial costs, broader economic effects, direct and indirect consequences, and impacts that fall unevenly across different groups. At this stage, transparency is essential, particularly regarding which effects are included, which are excluded, and the reasons for these choices.

The identified impacts are then quantified in physical terms where possible and monetised where credible valuation methods exist. Market prices may be used when they reflect opportunity costs, while non-market effects may require other valuation approaches such as avoided cost, replacement cost, or stated-preference methods. At the same time, not all impacts can or should be expressed in monetary terms, and non-monetised effects may therefore be retained as complementary indicators. Because costs and benefits often occur over long periods, they are discounted to present values using a chosen discount rate and then aggregated over the selected time horizon. The main summary measure is usually the net present value (NPV), which expresses the discounted value of benefits minus costs over time and is presented in equation 2.

$$NPV = \sum_{t=0}^T \frac{1}{(1+r)^t} (B_{it} - C_{it}) \quad (2)$$

where  $B_{it}$  and  $C_{it}$  are benefits and costs for alternative  $i$  at time  $t$ ,  $r$  is the discount rate, and  $T$  is the time horizon. NPV supports ranking of alternatives, while additional metrics (such as benefit-cost ratio) may be used to improve interpretability.

This can be used to compare and rank alternatives, sometimes together with additional indicators such as the benefit-cost ratio. Since the results of a CBA depend on assumptions and input values, the final step is usually a sensitivity and uncertainty analysis, in which key parameters such as the discount rate, the time horizon, and major valuation assumptions are varied to test how robust the conclusions are.

## 5.6 Environmental Justice

Since safe drinking water is a public health issue, the health benefits of protection and provision should be distributed fairly in a just society. Environmental justice (EJ) scholarship emerged from evidence that environmental burdens such as toxic waste sites, landfills, and other pollution sources are not randomly distributed, but tend to concentrate in marginalised communities, thereby reinforcing existing socio-economic and racial inequalities (Malin et al., 2019). This distributional concern has been central to EJ since the movement's early focus on unequal exposure to hazardous facilities and unequal environmental protection. In this context, Boone et al. (2009) define a just distribution as “an equal distribution of benefits and burdens among individuals or groups”, a formulation that provides a direct entry point for assessing who bears the costs of environmental risk and who receives the benefits of risk reduction.

Applied to drinking water, EJ shifts attention from average conditions to disparities in water quality, compliance, and protection across communities. Over the past decade, U.S.-based studies have documented socio-economic and racial patterning in drinking-water contamination and regulatory performance and have proposed conceptual frameworks for explaining how such disparities arise and persist. For example, Balazs et al. (2011) examine social disparities in nitrate contamination in community water systems, and Balazs and Ray (2014) develop a “drinking water disparities framework” explicitly linking drinking water to environmental injustice. Related work has also analysed how race, ethnicity, and socio-economic status intersect in Safe Drinking Water Act compliance outcomes (Switzer and Teodoro, 2018). Taken together, this literature indicates that EJ is an increasingly used lens in drinking-water research and policy, but most empirical evidence and conceptual development has, so far, been concentrated in the U.S. context.

If environmental justice is to be considered a relevant perspective for source-water protection in Sweden, the necessary starting point is descriptive rather than normative. This means first establishing where Sweden currently stands in distributional terms by examining whether systematic differences exist between population groups in exposure, protection, or service conditions, and whether the burdens and benefits of protection decisions are allocated unevenly. Such a baseline is necessary before it is possible to judge whether, and in what way, environmental justice considerations can be meaningfully integrated into Swedish source-water protection practice.

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## 6 DSR FRAMEWORK – RESEARCH

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*This chapter presents the research activity of the thesis in terms of the Design Science Research (DSR) framework. Drawing on the needs identified in the practical environment and the methods introduced in the knowledge base, it explains how selected approaches were adapted into practice-oriented artifacts for groundwater protection. The chapter focuses on the central DSR activities of develop/build and justify/evaluate, showing how the artifacts were designed to address identified implementation challenges, how they were operationalised in a Swedish drinking-water protection context, and how they were evaluated. In this way, the chapter forms the bridge between the environment and knowledge base on the one hand and the thesis results on the other.*

### 6.1 Design Cycle Description

In the DSR framework, the design cycle refers to the iterative process of building and evaluating artifacts in response to identified practical needs. In this thesis, the design cycle consisted of translating selected methods from the knowledge base into practice-oriented artifacts for groundwater protection and assessing them in realistic settings.

The build and develop part of the design cycle involved adapting each selected method to the needs of Swedish drinking-water protection practice. This meant defining what the method needed to achieve in practice, simplifying or restructuring it where necessary, and translating it into an operational form that practitioners could use more directly. The resulting artifacts took different forms depending on the method area, including a probabilistic modelling workflow, an ecosystem-services based assessment structure, a screening tool, a cost-benefit framework, and a geospatial analysis approach.

The justify and evaluate part of the design cycle was carried out through case studies and applications reported in the appended papers. These evaluations were used to assess not only the technical functioning of the artifacts, but also their usefulness, clarity, and relevance in practice. In addition, a national practitioner survey was conducted to provide a broader basis for reflecting on the design cycle across the thesis as a whole. Responses from consultants, municipalities, water utilities, and County Administrative

Boards were used to support the reflection on strengths, limitations, and future development presented in later chapters. Table 7 summarises how each method area was translated into an artifact and where its development and evaluation are reported.

**Table 7.** Knowledge-to-artifact translation in this thesis, summarising for each Chapter 5 method area the environment focus, the knowledge base used, the operationalisation focus, the resulting artifact form, and the location of reported outcomes.

<b>Knowledge area from Chapter 5</b>	<b>Environment focus (what it must fit in WPA work)</b>	<b>Operationalisation (focus in this thesis)</b>	<b>Artifact form</b>	<b>Outcomes reported in</b>
<b>AEM-based delineation</b>	Delineation and zoning tasks requiring defensible, mappable boundaries under limited site data	Feasible workflow, explicit assumptions and uncertainty, WPA-compatible outputs	Modelling workflow	Chapter 6.2 (Paper I)
<b>Ecosystem services</b>	Benefit identification and communication in planning and documentation; consistent screening across sites	Bounded, drinking-water specific structure and stepwise documentation procedure	Assessment procedure; browser-based tool	Chapter 6.3–6.4 (Papers II–III)
<b>Risk assessment</b>	Prioritisation of hazards and justification of measures; traceable documentation	Standardised recording and comparison to support prioritisation and traceability	Structured risk assessment approach	Chapter 6.3 (Paper II)
<b>Cost-benefit analysis</b>	Comparison of protection alternatives where costs are visible but benefits need justification	Transparent and documentable benefit-side structure for comparing alternatives	CBA framework	Chapter 6.5 (Paper IV)
<b>Environmental justice</b>	Establishing a descriptive baseline on distributional patterns to inform planning and prioritisation	Replicable descriptive analysis using workable indicators and consistent linkages	Geospatial analysis protocol	Chapter 6.6 (Paper V)

## 6.2 Paper I: Accessible Probabilistic Modeling of WHPA

Paper I presents an accessible workflow for probabilistic delineation of wellhead protection areas (WHPAs). The paper develops a practical way to include parameter uncertainty in WHPA delineation by combining Monte Carlo simulation with the Analytic Element Method (AEM) in an open-source Python environment, and by summarising results as GIS-ready, percentile-based WHPA envelopes.

In the study, the approach is implemented by building on the open-source AEM modelling library TimML (Bakker, 2024) to run groundwater flow modelling and

reverse particle tracking for a time-of-travel based WHPA criterion. A dedicated Monte Carlo component is added, together with a pre-processor that defines uncertain hydrogeological inputs as probability distributions and a post-processor that converts outputs into GIS products. Across repeated model realisations, uncertain parameter sets are sampled and assigned to TimML runs, reverse pathlines are generated, and the resulting ensemble of capture-zone realisations is summarised as percentile-based WHPA envelopes (illustrated using multiple percentiles to represent increasingly conservative delineations). The workflow is demonstrated for the Varnum aquifer in Sweden and benchmarked against an existing deterministic numerical model for the same site.

The developed method shows that uncertainty-aware WHPA delineation can be carried out with modelling choices that remain accessible for practitioners, and that the resulting percentile envelopes provide a clear and transparent way to represent how WHPA extent varies across plausible conditions.

### **6.3 Paper II: Combining Ecosystem Services with Risk Assessments for Drinking Water Protection**

Paper II presents an approach for integrating the ecosystem services (ES) framework into risk assessments for drinking-water protection, so that decisions are informed not only by risks to the drinking-water supply but also by the wider set of services provided by the water source. The paper introduces the concept of water system services (WSS) as a drinking-water specific adaptation of ES and proposes a structured way to include these services in a Water Safety Plan style risk assessment.

In the study, the ES classification CICES is used as the starting point to develop a region-specific list of services tailored to drinking-water sources. The paper describes a stepwise procedure to compile the Swedish WSS list, including defining system boundaries, reviewing and revising CICES service classes (excluding irrelevant classes, merging similar ones, and adding missing water-related services), adding practical examples, and conducting an iterative review with both researchers and practitioners. The resulting WSS list is then applied in a Swedish case study (the Skallsjö aquifer). Services are identified using a checklist approach supported by remote sensing and site visits, and hazards to the municipal water supply are identified using the TECHNEAU hazard database (Beuken et al., 2008) together with local data and expert input. Finally, the services and hazards are combined in an assessment matrix where risk is scored for each hazard service pair using a risk priority number approach consistent with Water Safety Plan practice.

The study shows that the case study aquifer provides multiple water system services across provisioning, regulating, and cultural categories, while being exposed to multiple hazard sources within the assessed area. The main output is an assessment matrix that contrasts hazard sources with their potential impacts on each service, allowing risks to

be viewed across services rather than only for drinking water. The results illustrate how this extended framing changes what is visible in the assessment, by highlighting which hazards contribute most to overall risk across services and by making synergies and trade-offs between protection measures and different services explicit.

## **6.4 Paper III: A Tool for Screening Groundwater Ecosystem Services**

Paper III presents an automated screening tool for groundwater ecosystem services at Swedish drinking-water sources. The paper introduces a practitioner-oriented application that retrieves and processes open national geodata for any user-defined area in Sweden and uses the results to pre-populate a structured ecosystem services assessment.

In the study, the tool is implemented as a local Streamlit application distributed via GitHub. Users define an area of interest by drawing it on an interactive map or by uploading a boundary file. The tool then automatically retrieves and processes the most recent relevant national geodata for the selected area and uses these data to pre-populate a groundwater-specific Swedish Water System Services (WSS) list (mapped to CICES) together with short evidence summaries. Services that cannot be derived from open data are completed through a short in-app questionnaire and manual notes. The main output is an Excel workbook documenting the screening, complemented by exported GIS layers for follow-up mapping.

The study shows that groundwater ecosystem service screening can be carried out in a consistent and time-efficient way by combining automated indicator extraction with a short, guided step for local input. The resulting outputs provide a compact checklist-style overview of groundwater-related services within the area of interest, where each service is documented with either an automatically generated evidence summary or a brief user-provided note, and the underlying spatial layers are available for direct use in standard GIS software.

## **6.5 Paper IV: Cost-Benefit Analysis for Water Protection Areas**

Paper IV presents a framework for applying cost-benefit analysis (CBA) to Water Protection Areas (WPAs) in a way that makes the benefits of protection more explicit and defensible. The paper addresses a common practical problem in WPA planning: while costs and compensation mechanisms can often be estimated, the long-term and diverse benefits of protection are difficult to identify, quantify, and communicate in a structured way.

In the study, we developed an integrated, ecosystem services-based CBA approach that links protection decisions to plausible contamination pathways and their consequences. An ecosystem services assessment is used to establish a comprehensive inventory of potential benefits that may be affected by agricultural contamination and by protection measures. Event tree analysis is then used to structure contamination scenarios, connect them to service impacts, and assign probabilities to alternative outcomes. This provides the basis for probabilistic benefit estimation, which can be carried through to a CBA comparison of alternative protection strategies and highlight where assumptions and data needs matter most.

The study shows how an ecosystem services-based CBA can make WPA planning more workable for practitioners by providing a clear structure to compare protection options and to document both costs and benefits in a transparent way. By making the benefit side explicit, the framework supports justification of restrictions and compensation and provides a reproducible basis for prioritising measures under limited time and resources.

## **6.6 Paper V: Exploring Environmental Justice for Drinking Water in Sweden**

Paper V examines whether socio-economic differences are associated with drinking-water access and service conditions in a Swedish context, using the extended Gothenburg region as a case study that includes both municipal drinking-water supply (MDWS) and private wells. While drinking-water disparities have been documented in several countries, comparable assessments are missing for Scandinavia. The paper therefore asks whether socio-economic indicators are associated with (a) reliance on private wells versus municipal supply and (b) differences in municipally delivered service conditions, including water quality indicators, water price, and pipe breaks.

In the study, we conducted a geospatial analysis that links drinking-water supply information (municipal service areas and private well locations) with socio-economic indicators. The analysis quantifies how these indicators differ between populations relying on private wells and those connected to municipal supply, and it examines whether socio-economic patterns are also associated with municipal service indicators such as water quality examinations, pipe breaks, and water tariffs.

The study shows that reliance on untreated drinking water from private wells is slightly more common in socio-economically advantaged communities. Within municipal supplies, broad associations between socio-economic indicators and service metrics are generally weak, but comparisons across municipalities indicate higher pipe-break frequencies and more water-quality test results with noted issues in poorer municipalities. Overall, the paper demonstrates how combining supply data with socio-economic and service datasets can make disparities visible in a structured way and can support prioritisation of infrastructure improvements and planned connections of currently self-supplied areas.

## 6.7 Results of the Practitioner Survey

The main survey results are briefly summarized below, while detailed results are presented in Appendices A and B. In this thesis, the term decision-makers refers to water resources managers working in municipalities, County Administrative Boards, government agencies, and water utilities.

The results show that the consultant group was highly specialized, with most respondents working primarily in technical roles, having long experience with water protection areas, and a strong background in hydrogeology. Familiarity with hydrogeological methods was generally high, including awareness of AEM, whereas regular use of MODFLOW appeared less common. This suggests that consultants are not primarily asking for greater technical sophistication in itself, but rather for approaches that are usable, defensible, and efficient under real project conditions.

The decision-maker group, in contrast, was more mixed in technical background and more strongly oriented towards review, governance, and decision-making functions. Many respondents had some familiarity with hydrology, hydrogeology, and uncertainty analysis, but not necessarily at an advanced level. This helps explain why decision-makers placed particular value on clarity, transparency, and recommendations that can be interpreted, and justified in formal decision contexts.

Across both groups, the clearest common finding was that practical usefulness matters more than technical sophistication alone. Consultants ranked uncertainty analysis, direct usability with national data, and open access as the most important characteristics of a useful tool, while speed was of relatively low importance. Decision-makers, in turn, prioritized effective protection and clear recommendations over technically detailed or strongly model-based results. Together, these findings suggest that advanced methods are valued when they support practical decisions, but not when they increase complexity without improving usability.

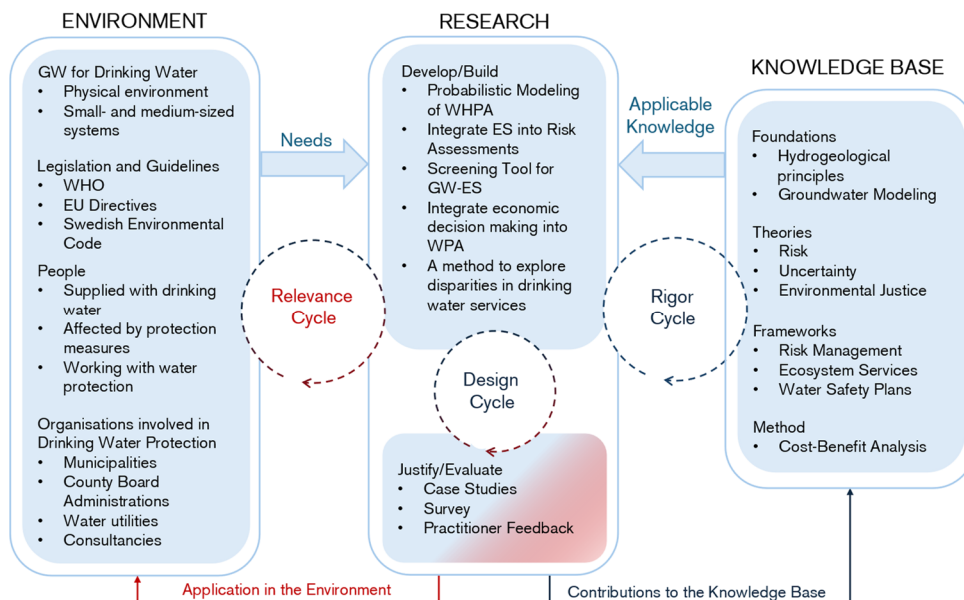
The results further show that decision-makers prefer conventional and reviewable outputs, especially written reports, geodata, and visual summaries, and that their trust in results depends mainly on methodological transparency, clear assumptions, and understandable input data rather than on the consultant's reputation alone. Ecosystem services, by contrast, did not emerge as an easy entry point for either group. Decision-makers often viewed them as potentially relevant but difficult to integrate, while consultants were generally more skeptical and frequently did not see a clear practical benefit.

Finally, the consultants' free-text responses pointed to a consistent set of implementation bottlenecks, including insufficient data, long and complex processes, uncertainty in zoning and risk assessment, communication difficulties, institutional friction, and the challenge of balancing sufficient protection against overregulation. Several responses also stressed that modelling may appear more certain than it is, and that practical protection often depends as much on follow-up measures and risk reduction in practice as on delineation itself. The decision-makers' free-text responses

highlighted similar implementation barriers, but with stronger emphasis on resource limitations, low priority, political resistance, administrative complexity, unclear guidance, and difficulties in translating risk analysis into workable regulations and supervision. They also pointed to recurring communication challenges in explaining and motivating protection measures to politicians, landowners, and the public. Taken together, the results suggest that the main implementation gap is not simply a lack of advanced methods, but a lack of approaches and tools that are transparent, trusted, and workable under the institutional and practical constraints of routine water protection practice.

## 7 DISCUSSION

This chapter discusses the contributions of the thesis, both in terms of the individual papers and the overall Design Science Research approach and reflects on the developed artifacts as well as the limitations of the methods used. Figure 10 provides an overview of what has been accomplished within the thesis and which parts of the DSR process are not concluded or should be further refined. The chapter then uses the DSR framework to structure the discussion of future work, while the survey results help identify remaining practitioner needs and indicate which directions should be prioritised in continued research.



**Figure 10.** Design Science Research as applied in this thesis, indicating completed and remaining steps in the research process. Blue elements represent work carried out in the thesis, while red elements represent future work needed to further close or update the relevance and design cycles.

## 7.1 Contributions of the Thesis

Across the thesis, the main contribution to implementation is the translation of methods that are often too technical or too fragmented for routine use into workflows, tools, and framings that better fit how WPAs are actually planned. The contribution is both practical and methodological. On the practical side, the work strengthens three parts of the WPA process that often create difficulties in implementation. These include delineating protection zones under uncertainty, identifying what is at stake beyond the drinking-water service alone, and making trade-offs and priorities explicit for communication with decision-makers and stakeholders. Together, the individual studies form a coherent chain from hydrogeological uncertainty, through risk and service consequences, to decision support and legitimacy. On the methodological side, the thesis shows how Design Science Research can be used to structure the development of implementable support for drinking-water protection.

### **Paper I: Probabilistic WHPA delineation using AEM and Monte Carlo simulation**

This paper improves WPA implementation by making uncertainty-aware capture zone delineation feasible for small and medium-sized supplies that cannot justify a full numerical modelling effort. The workflow reduces the practical barrier to using defensible modelling by integrating pre-processing, modelling, and GIS-ready outputs in one reproducible Python environment. A key implementation benefit is that the method makes the chosen level of precaution explicit by providing percentile-based WHPA envelopes rather than a single deterministic line. This supports risk-informed zoning decisions and facilitates communication with stakeholders, because the spatial implications of uncertainty become visible and discussable rather than implicit.

### **Paper II: Water System Services as an operational ecosystem services framing for drinking-water protection decisions**

This paper advances the implementation of WPAs by expanding in a structured way the range of water-based services that can be considered in the planning process. Conventional risk assessments often focus narrowly on the supply of drinking-water, while protection measures affect multiple services creating trade-offs and synergies. The WSS concept provides a practical, context-specific list of services that is compatible with WPA workflows. Its practical application can facilitate the justification of protection measures by showing the range of impacts beyond the core supply function. In implementation terms, WSS facilitate negotiation and support broader acceptability, because they provide a shared language for consequences that different stakeholders care about.

### **Paper III: A screening tool to reduce transaction costs of WSS assessment**

This paper addresses a day-to-day implementation barrier that is the time and effort required to compile indicators and produce a consistent service assessment record across many sites. By integrating data retrieval and reporting into a single workflow, the tool shifts effort away from repeated data handling and toward interpretation and

documentation, which is where practitioner judgement is more needed. The tool also helps ensure that the data used are current by drawing directly from providers at runtime.

#### **Paper IV: A repeatable CBA framework linking risk, services, and economic evaluation**

This paper advances implementation by showing how economic evaluation can be made more systematic and traceable in WPA planning, especially where restrictions trigger compensation debates. Applying the logic of Event Tree Analysis, the study develops a framework to connect contamination pathways to service impacts and then to valuation choices. This approach limits the bias of purposive selection of benefits. At the same time, the paper illustrates why robust CBA is challenging in routine practice: data needs are high and uncertainty handling increases complexity.

#### **Paper V: Environmental justice and distributional patterns in drinking-water service conditions**

This paper moves implementation forward by adding a distributional lens to drinking-water protection and infrastructure planning. It shows that inequalities can be local and therefore easy to miss in regional averages, and it demonstrates how combining utility performance indicators with private well distribution and socio-economic data provides a more precise picture of who receives what type of service and under what conditions. This matters for implementation because WPA decisions and infrastructure investments increasingly sit in a context of affordability pressure and public scrutiny. An environmental justice perspective can act as an early-warning tool, highlighting where service quality or cost burdens risk becoming uneven before problems become entrenched.

#### **Design Science Research as a framework for method development in groundwater protection**

The second strand of contribution lies in the thesis' methodological approach through the explicit use of Design Science Research to organise how methods and concepts are translated into implementable support for water protection area work. Rather than treating translation as an informal "last step" after scientific results are produced, DSR provides a structured pathway from identifying practitioner needs and implementation constraints, to selecting and adapting candidate methods, to building concrete artifacts such as workflows, tools, and templates that can be tested in real settings. In this thesis, DSR therefore functions as a bridge between theory and practice where it makes the design choices visible, documents why particular simplifications are made, and treats usability, transparency, and fit with planning routines as explicit quality criteria alongside scientific credibility.

DSR also proves useful because it forces evaluation to be framed in terms that matter for implementation. Instead of asking only whether a method is technically sound, it becomes possible to ask whether it is useful under real resource constraints, whether it reduces transaction costs, whether it supports communication and justification, and whether it introduces new limitations. This strengthens the overall contribution by

turning the papers from isolated method demonstrations into a coherent set of practitioner-facing artifacts with a shared logic of development and evaluation. At the same time, the use of DSR highlights a core trade-off that runs through drinking-water protection work: improving usability often requires simplification and standardisation, which can reduce flexibility or theoretical robustness. Making that trade-off explicit is itself a contribution, because it clarifies what the designed methods can reasonably claim and where additional work is needed for broader implementation.

## **7.2 Reflections on the Identified Methods and Limitations**

This section reflects on limitations of the individual methods employed in the thesis and the knowledge base from which they are drawn. Across the thesis, the selected methods advance the implementation of groundwater protection by making assessments more structured, transparent, and easier to use in practice. At the same time, methods do not only support decisions but also influence how protection problems are framed, what becomes visible in the assessment, what can be compared across cases, and what is easier to prioritise. Reflecting on these limitations is therefore not only about identifying where the methods are useful, but also about understanding the assumptions they bring into the assessment and the aspects of groundwater protection that may remain less visible.

This is already apparent with the introduction of probabilistic methods. Probabilistic WHPA delineation and Monte Carlo based risk and cost estimates are useful because they make uncertainty more explicit and allow the exploration of results sensitivity. That is a clear step forward compared to deterministic outputs. But the results still depend on choices about probability distributions, parameter ranges, and model structure. These choices are not only technical, but they also reflect data limitations and user bias. As discussed by Aven (2010) and by Parker and Risbey (2015), probabilistic outputs may be interpreted by decision makers as more objective and more precise than they really are. Their formal use can create an impression of mathematical authority, even when the assessment still depends on limited knowledge, and subjective choices. Additionally, uncertainty in model outputs can undermine stakeholders' confidence in management plans and make decision-makers less willing to base actions on them (Borowski and Hare, 2007).

The ecosystem services framework helps broaden the assessment beyond the drinking water service alone, but it also comes with its own assumptions and limitations. At its core, the framework is anthropocentric, since services are defined through their contribution to human well-being, and its application inevitably involves choices about which services and values are recognized, highlighted, and carried into decision making (Jax et al., 2013; Schröter et al., 2014). Moreover, the ecosystem services assessment conducted in this thesis was necessarily static and local. Although a pragmatic simplification, that means that temporal dynamics and cross-scale effects were only partly captured. This is particularly relevant for water sources since ecosystem services vary across space and time. In this context, static snapshot assessments can quickly become incomplete with remote or spill-over effects often insufficiently understood (Vári et al., 2021). Services beyond the local study area, such as carbon sequestration or

broader climate regulation, were therefore not included. A further limitation is that an ecosystem services assessment can only capture services that are already known and evident. For groundwater systems, this remains a moving field. Continued advances in groundwater ecology and biodiversity research are still expanding the understanding of groundwater ecosystem functioning and groundwater-related services, which suggests that the benefits of water protection are likely underestimated.

A similar problem can be seen with economic evaluation. CBA is useful because it makes assumptions explicit and supports a more transparent comparison of options, which is often required in WPA decision support. At the same time, the method is grounded in a utilitarian and consequentialist logic, where options are judged based on the monetised benefits and costs (Kelman, 1981). This makes trade-offs easier to compare, but it also gives less space to benefits that are non-market, long-term, uncertain, or difficult to value in monetary terms (Ackerman and Heinzerling, 2002; Wegner and Pascual, 2011). That is particularly relevant for groundwater-dependent ecosystems and for broader social and cultural values associated with water environments, which are not always well captured through willingness-to-pay or individual utility-based approaches. CBA is therefore best seen as a tool for clarifying trade-offs, not for capturing the full range of values relevant to WPA decisions.

Risk assessment frameworks are also subject to important limitations. These methods are useful because they help structure the analysis and make assumptions about hazards, pathways, barriers, and consequences more explicit. That is a clear strength in the planning of groundwater protection, where risks are often complex and difficult to compare. At the same time, structured risk assessments tend to work best for risks that can be clearly described and bounded. Many important WPA problems do not fully fit that logic. Diffuse pollution, long travel times, changing land use, climate effects, and weak enforcement may strongly influence the actual risk, but they are often more difficult to represent within formal assessment frameworks. As a result, risks based on clear data and more defined causal chains may receive greater attention than uncertainties that are equally important but less measurable. The limitation is therefore not whether the method works, but what kinds of risk it brings into focus and what kinds of uncertainty tend to remain outside the structure.

Standardisation improves comparability across sites, but it also simplifies a method. The WSS list and screening tool make assessments more systematic and easier to conduct and document. That is a real advantage in WPA work, where time and institutional capacity are often limited. But the same standardisation that makes the method usable also sets limits on what it can capture. Groundwater dependent services are shaped by local hydrogeological conditions, ecological interactions, land use, and governance arrangements that vary from place to place. A general list cannot fully reflect that variation. The risk is thus not standardisation itself, but the temptation to treat a standardised tool as complete. In practice, the main value of the tool is that it provides a shared starting point and a structure for discussion. It does not remove the need for

site-specific interpretation, and it does not guarantee that all relevant mechanisms have been considered.

There is also a risk of looking at groundwater protection too narrowly through the lens of water protection areas. In practice, groundwater protection is often translated into formal planning in the form of a water protection area, partly because these fit existing legal and administrative structures and are therefore easier to anchor in planning and decision-making. However, once protection is framed in that way, the needs that are voiced and the knowledge that appears relevant are also shaped by the expectation that the answer should be a WPA. That can make other forms of protection less visible, including indigenous and community-led approaches that are not centred on formal zonation alone. Examples of alternative forms are the protection of recharge areas and regulation of forest use around springs in Besao in the Philippines (Bang-Oa, 2006), the combination of land zoning, sacred groves, and biodiversity maintenance in Meitei water management in north-eastern India (Laifungbam and Pinto, 2006), or watershed planning through the Ahupua‘a concept in Hawai‘i (Minerbi, 1999). It can also make less formal community-based practices easier to overlook, for example collective rules linking agricultural responsibilities to the protection of springs, watercourses, and catchments in Tagmachig in the Indian Himalayas (Wacker, 2006), or communal governance arrangements in which water is treated as a shared good rather than a privatised resource (Bang-Oa, 2006). These examples are not framed as WPAs, but they still organise land use, behaviour, and responsibility around water protection. A WPA is therefore an important instrument, but it should not be understood as the only legitimate way of organising groundwater protection.

Environmental and distributional justice are useful in groundwater protection because they shift attention from the resource alone to the people affected by service conditions and protection measures. In this thesis, this perspective is mainly valuable for exploring the “environment” side of the DSR framework by making the social context of water supply more visible. However, Balazs and Ray (2014) show that mapping unequal exposure to poor drinking water does not by itself explain why inequities arise or persist. They emphasise that drinking-water injustice is shaped by interacting natural, built, and sociopolitical factors across multiple levels, including hydrogeology, land use, governance, regulation, political power, and household resources. This makes environmental justice studies analytically complex and means that they rarely point to one single cause or one obvious policy fix. In that sense, justice-based analysis contributes to the implementation of WPAs not by providing operational knowledge directly applicable, but by advancing our understanding of the social setting in which groundwater protection happens. It provides a starting point for assessments and can be combined with other methods to support more actionable and better justified decisions.

However, the limitations do not only sit within the employed methods themselves. They also sit in the knowledge base from which methods are selected. What is available for groundwater protection is shaped by disciplinary traditions. Method selection therefore does not begin from a neutral set of options. It begins from a field that has already been

filtered, where some approaches are more readily recognised as rigorous than others. Some questions also attract more funding, and attention, while others remain less explored. This affects not only the type of methods available and used, but also how the problems are framed in the first place. The available knowledge base is therefore not simply incomplete. It is also shaped by institutional priorities and broader patterns in research agendas.

This, in turn, makes method development path dependent. Many of the contributions in this thesis build on established approaches and aim to make them more applicable in water protection practice. This is also consistent with a theory of change perspective, in which longer-term improvement is expected to emerge through smaller intermediate steps, and with the broader idea of incremental change (Harris, 2022; Lindblom, 1959). In practice, this often depends on methods already being familiar, credible, and possible to apply in real planning contexts. At the same time, working from existing approaches also means carrying forward some of their biases and boundaries. When method development proceeds through incremental improvement of recognised tools, it can also limit the space for alternative framings that may be better suited to improve groundwater protection. The methods developed here should therefore be understood as practical advances within an existing methodological landscape. They improve applicability, but they do not remove the need to question the boundaries of that landscape itself.

DSR as a research methodology for groundwater protection also deserves some reflection. It is useful because it provides a clear structure for linking practical problems to the development and evaluation of artifacts in applied science. That is a particular strength in groundwater protection, where there is often a gap between methodological development and practical implementation. At the same time, the framework originates mainly from information systems and other design-oriented fields, where artifacts, users, and evaluation settings are often more clearly bounded than in environmental practice. In groundwater protection, problems are shaped by long time horizons, diffuse risks, uncertain feedbacks, and multiple actors with different mandates and values. This does not make DSR unsuitable. Rather, it highlights the value of adapting the framework carefully to environmental problems, where implementation is slower, and the effects of an artifact may only become visible over time.

### **7.3 Where to Go from Here**

This thesis has developed a set of artifacts intended to support the implementation of water protection measures in practice. Seen through the Design Science Research framework, this means that the work has moved beyond problem identification and artifact development toward initial evaluation and dissemination. At the same time, the DSR cycles are not fully closed (see Figure 10). The relevance cycle and the design cycle are not complete, because the real test of the developed methods begins when they are taken up or rejected in practice.

For the relevance cycle, the next step is the application of the developed artifacts in the environment. The methods, tools, and frameworks developed in this thesis are now openly available, but their practical uptake will only become visible over a longer time frame. It remains to be seen which parts are adopted, by whom, and under which conditions. It is equally important to understand which parts are not used and why. Such practical uptake may confirm the current understanding of practitioner needs, but it may also reveal new needs, constraints, or unintended consequences. In that sense, the environment does not only receive the artifacts. It also responds to them and reshapes the problem space.

The design cycle is therefore also still ongoing. While the artifacts have been developed and evaluated through case studies, they still require further iteration with end users to ensure they keep being relevant. This is especially important because implementation of water protection measures is not simply a technical exercise. Even useful artifacts may fail to take hold if they do not fit existing or evolving administrative routines and practice. Future iterations should therefore focus not only on methodological refinement, but also on usability and an effort required for application in municipal and consultancy settings.

The role of consultants in the groundwater protection process deserves further attention. Previously, their work was mainly concerned with technical assessments, such as groundwater modelling, calculations, and the generation of hydrogeological data for decision making. In recent years their involvement has often extended further to include supporting public authorities' work after an WPA-application has been submitted, guiding stakeholder engagement, and in some cases contributing to the drafting of legal acts. This development is consistent with the broader rise of consultancy work in public administration discussed by Seabrooke and Sending (2022). One consequence is that outsourced expertise increasingly takes over tasks that were previously carried out within public agencies by civil servants or politicians. From this perspective, a stronger reliance on consultants may reduce in-house planning capacity and gradually reshape the problem space of groundwater protection. Future research could therefore examine the role of consultants more closely, map their position in the process, and better account for their influence, needs, and knowledge production in future groundwater protection research.

Important insights on emerging needs and areas that deserve greater attention in future research have been gathered through the stakeholder survey conducted for this thesis. One primary insight is that implementation cannot be understood as a purely technical task. In many cases, the main difficulty lies in stakeholder resistance and conflicts with land use interests. This suggests that the next generation of artifacts should support communication and negotiation as much as technical analysis. A useful direction would be to combine technical outputs such as WHPAs, risk assessments, and WSS assessments with more structured formats for dialogue, so that trade-offs become even clearer and the reasoning behind restrictions can be communicated more effectively.

Another important insight gained from the stakeholder survey concerns capacity building. The survey results suggest that familiarity with risk-based thinking and the broader logic of water protection is uneven among stakeholders. This matters because methods are unlikely to be applied consistently if the underlying concepts are not shared. Future work should therefore include training opportunities, but also educational material and templates that make the links between risk inventory, zoning, and protection provisions more explicit and easier to understand.

A further concern is the legal dimension of WPA implementation. This thesis focused mainly on developing technical and decision support artifacts, but the survey showed that the drafting of robust legal provisions is a major challenge in practice. Future work should therefore examine how protection provisions are formulated, where recurring legal difficulties arise, and whether more standardised support can be developed. This could include repositories of example formulations, analyses of common drafting problems, and better ways of organising collaboration between technical experts, administrators, and legal counselling.

A final group of issues refers to long timelines, staff turnover, and shifting political priorities. These are not problems that can be solved by a better model alone, yet they strongly influence whether WPA work is completed and maintained over time. This points to the need for more attention to process design, including documentation routines, handover practices, and simple decision records that preserve continuity when projects extend over several years.

Overall, the next step is not to move away from the artifacts developed here, but to continue closing the DSR cycles through use, feedback, and refinement. The relevance cycle should be completed by observing how the artifacts perform in practice. The design cycle should continue through iteration with practitioners. The rigor cycle should be strengthened by feeding these experiences back into the knowledge base. In that way, research can move beyond simply showing that the artifacts are feasible, and instead examine when they become useful, accepted, and durable parts of WPA practice.



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## 8 CONCLUDING REMARKS

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Humans have had to make decisions about water since the beginning of civilization. The choice, for example, to drink from a nearby but unknown river or walk further to a familiar spring, to look for wood and boil water before consumption or drink it as it is, was always part of everyday routine. But the problems have changed since ancient times and so has decision-making. What was once largely intuitive and experience-based is now expected to be data-driven, computer-aided, and often justified in economic terms.

The mere act of taking a decision is simple. Taking a responsible robust decision providing optimal outcomes is not. Groundwater protection is an interdisciplinary field where legal regulations, environmental goals, the feasibility of technical solutions, costs, ethics, and politics must be carefully weighed, and consequences analysed. Furthermore, decision-makers frequently attempt to achieve multiple yet conflicting objectives. There is rarely a single optimal solution. Instead, there is a set of plausible options, each with different implications for risk, cost, and acceptability. Integrating such dissimilar information calls for transparent methods and systematic structures.

This thesis provides practical methods and decision support elements that align with the realities of water protection work in Sweden. It strengthens technical defensibility (probabilistic delineation), broadens and operationalises what benefits and consequences are considered (WSS), reduces transaction costs of applying these ideas at scale (screening tool), and provides a structured way to connect risk outcomes to economic arguments when needed (CBA framework), while showing that legitimacy depends also on distributional considerations (environmental justice). The overall implication is that improving water protection implementation is not only about better science, but about making methods usable, transparent, and easily communicable within institutional and political constraints.

In the end, society will need to decide how to protect groundwater sources, even without having complete information. Or, to use a well-known German phrase: "*The necessity to decide extends further than the possibility to understand.*"<sup>1</sup>

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<sup>1</sup> *German:* „Die Notwendigkeit zu entscheiden reicht weiter als die Möglichkeit zu erkennen.“ A quote of which the author is unknown but that is often attributed to Immanuel Kant.



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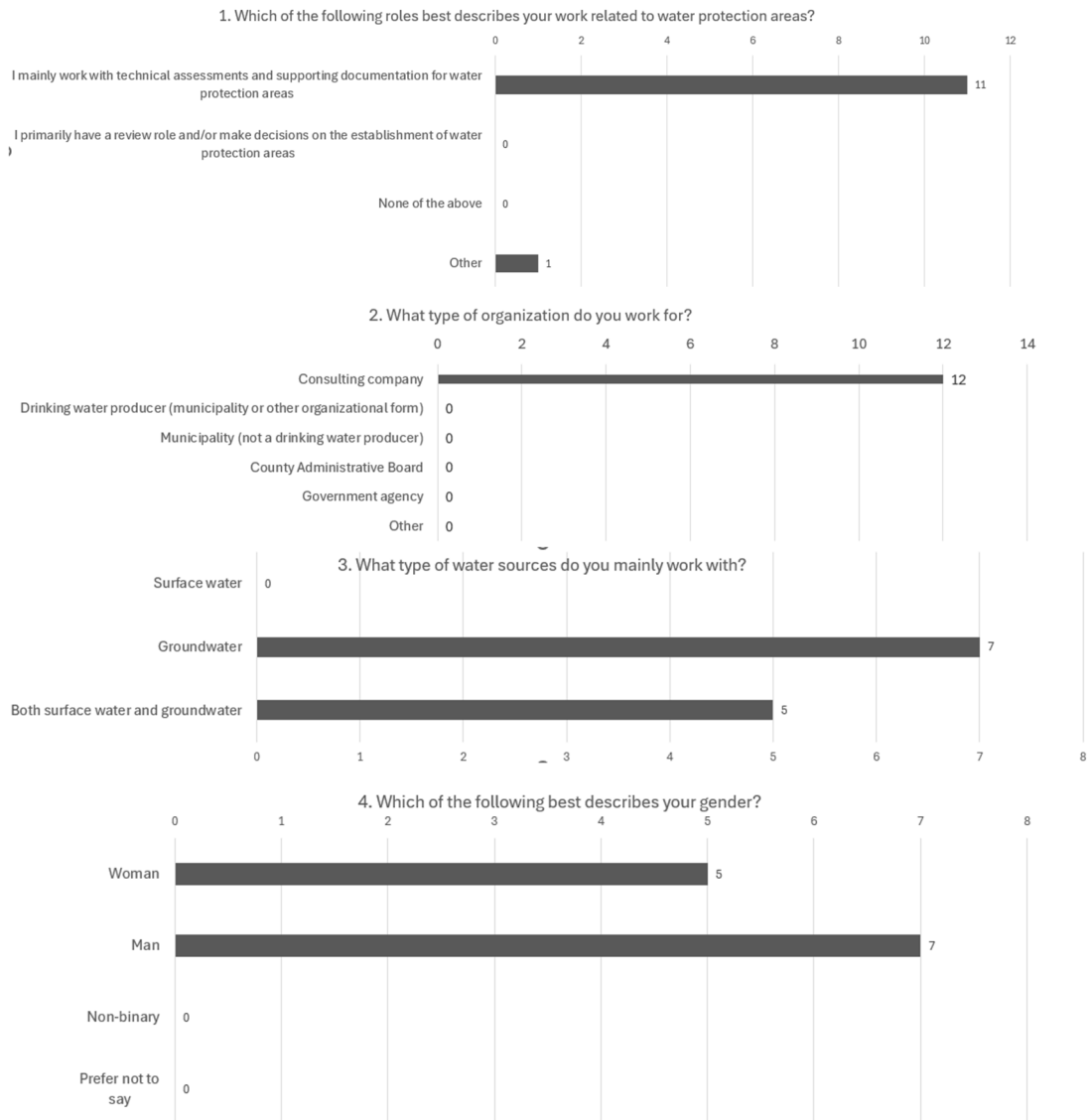
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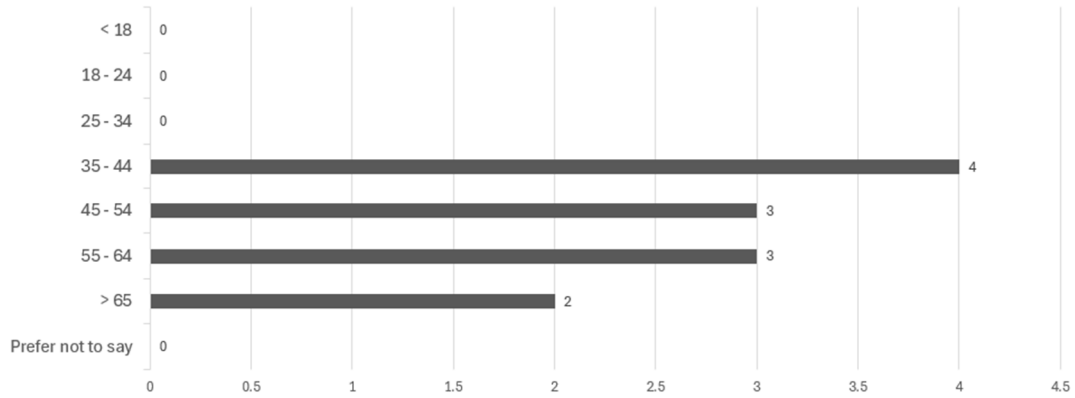
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# APPENDIX A

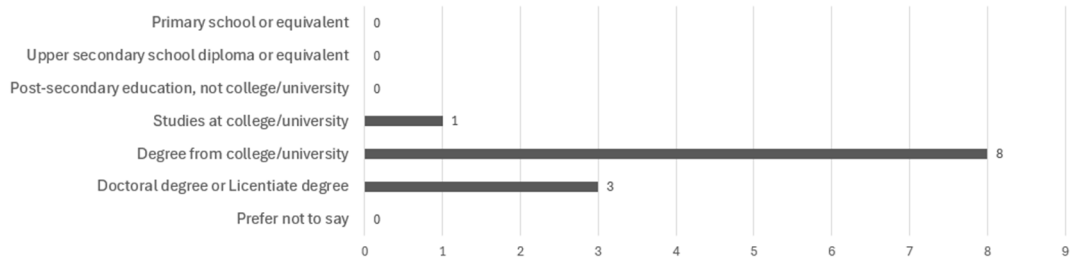
## Survey 1, directed at consultants.



5. How old are you?

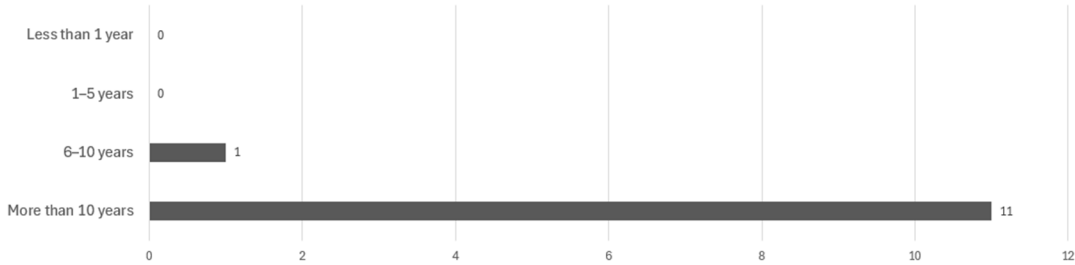


6. What is your highest completed level of education?

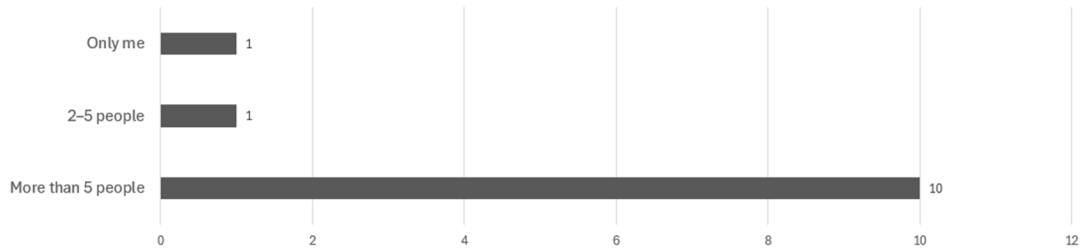


7. What is your educational field? (Please state the main subject area or discipline of your professional training or academic degree)

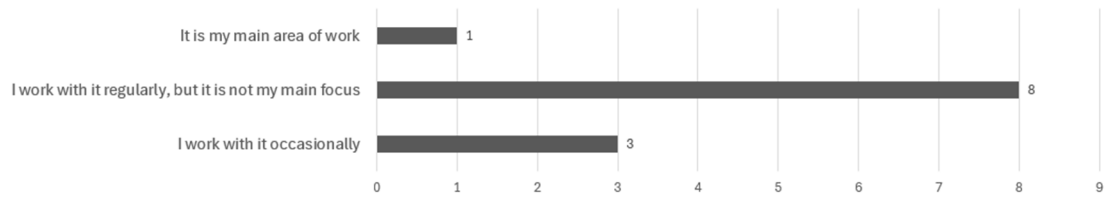
8. How long have you worked with water protection areas?



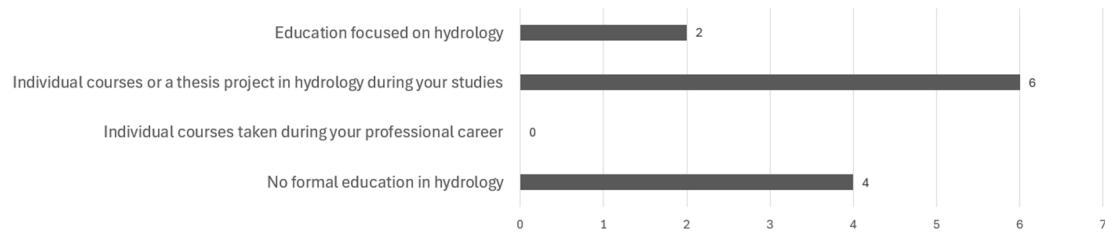
9. How many people in your organization work with water protection areas?



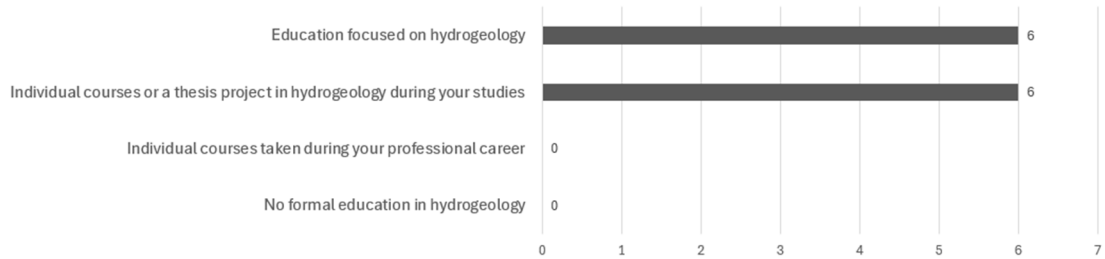
10. How would you describe your work with water protection areas (development, supervision, etc.)?



11. How would you describe your education in hydrology?



12. How would you describe your education in hydrogeology?

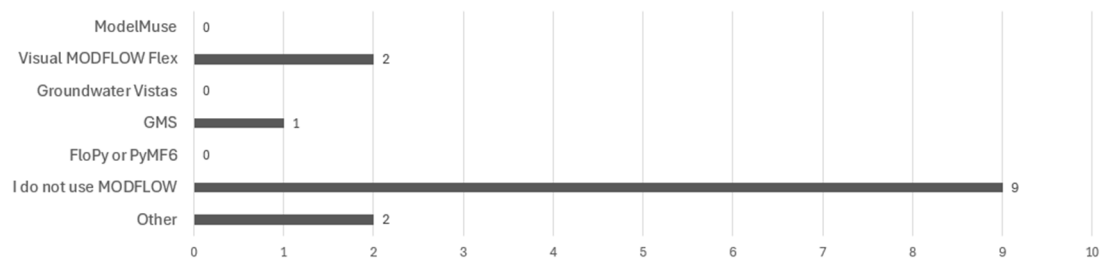


13. How would you assess your level of knowledge regarding the following groundwater modeling software?

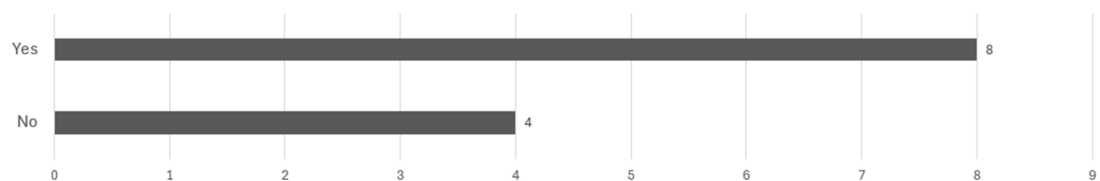
None Basic Advanced Expert



14. If you use MODFLOW, which interface do you mainly work with?  
(Multiple answers possible)



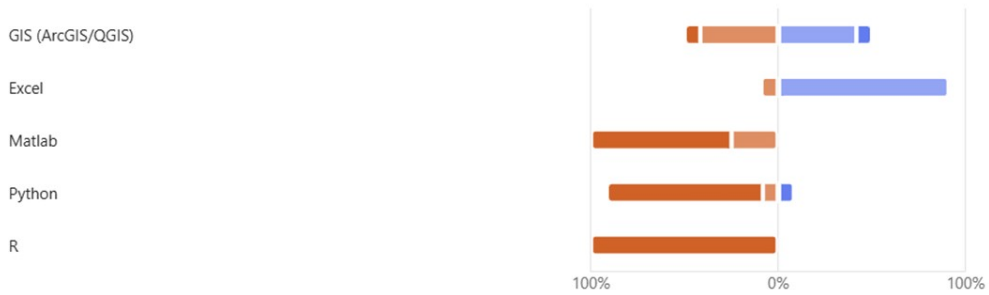
15. Are you familiar with the Analytic Element Method (AEM – Analytic Element Model) in groundwater modeling?



## Appendix A

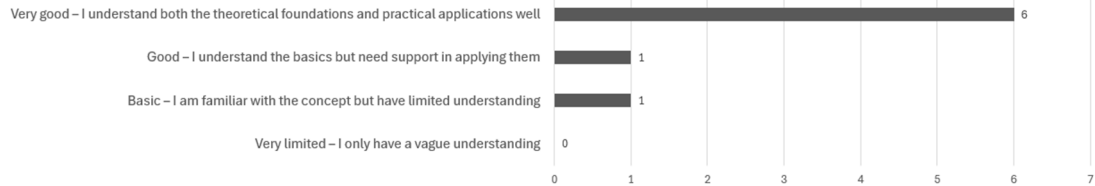
16. How would you assess your level of knowledge in the following software/programming languages?  
(Please select one option for each row)

● None ● Basic ● Advanced ● Expert



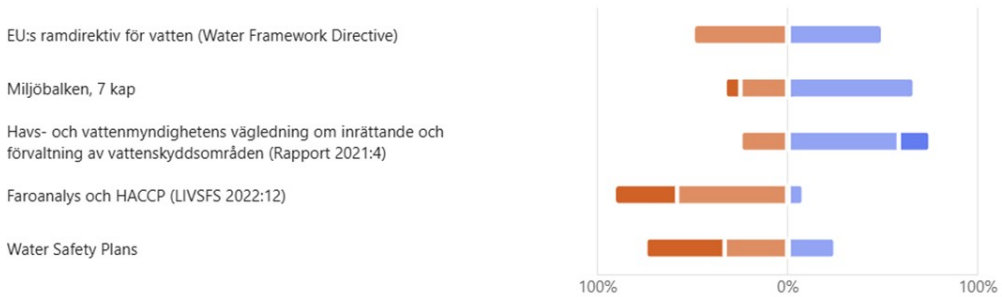
17. How would you describe your general knowledge of uncertainty analysis?

(This includes understanding of how uncertainty is assessed, quantified, and managed in the risk assessment of delineating water protection areas.)



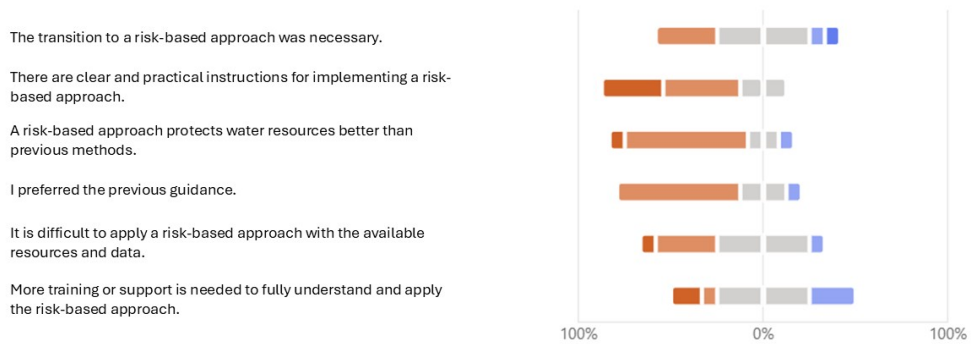
18. How familiar are you with the following guidelines, laws, or tools for working with water protection areas?  
(Please indicate your level of knowledge: None, Basic, Advanced, Expert)

● None ● Basic ● Advanced ● Expert

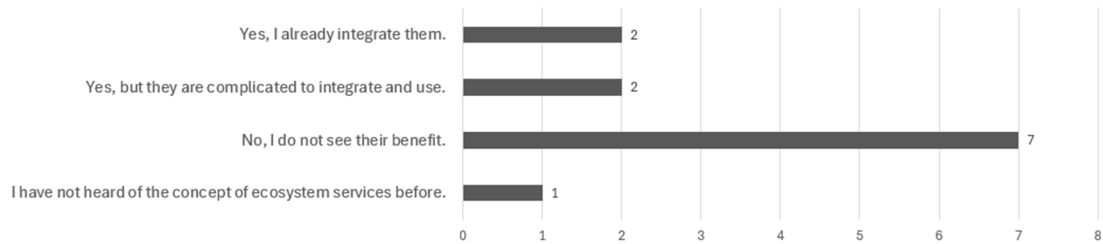


19. Sweden now has new guidelines for how water protection areas should be established and managed. These are set out in the Swedish Agency for Marine and Water Management's guidance (Report 2021:4). The guidelines emphasize a more risk-based approach to water protection areas. To what extent do you agree with the following statements?  
(Please indicate the degree to which you agree: Do not agree at all, Agree partly, Agree mostly, Agree completely, Do not know)

● Disagree ● Agree partly ● Agree mostly ● Agree completely ● Do not know



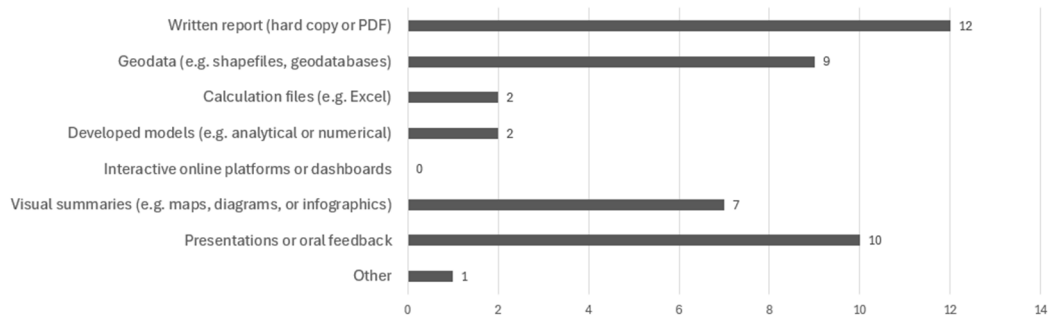
20. Do you think ecosystem services should be used in the planning of water protection areas?



21. Briefly describe what your workflow usually looks like when you prepare supporting documentation for the establishment of a water protection area. (e.g. assignment, site visits, data collection, calculations using method X, etc.)

22. What tools or software do you use in your work with water protection areas? (e.g. internal Excel document, risk assessment software)

23. In which formats do you usually deliver the results? (Multiple answers possible)

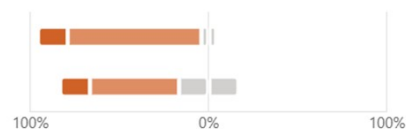


24. Do you usually have enough time (and budget) to carry out the work in the way you believe it should be done in the following situations?

Always enough time  
  Usually enough time  
  Usually not enough time  
  Never enough time  
  Do not know

When a new water protection area is to be designed and established

When an existing water protection area is to be reviewed or updated



25. Imagine that a new tool is being developed for delineating water protection areas. Rank how important you consider the following characteristics of such a tool. (Top = Most important, Bottom = Least important)

1	Includes uncertainty analysis
2	Directly usable with national data
3	Open source and free of charge
4	Has a graphical user interface
5	Requires minimal additional training or specialized knowledge
6	Fast results

Appendix A

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26. Which aspects are most important to you regarding results from investigations, etc. used as supporting documentation for water protection areas? Rank the options below from most to least important. (Top = Most important, Bottom = Least important)

1	Clear recommendations
2	Effective protection
3	Technically detailed results (including margins of error and uncertainties)
4	Minimal restrictions
5	Results based on modeling

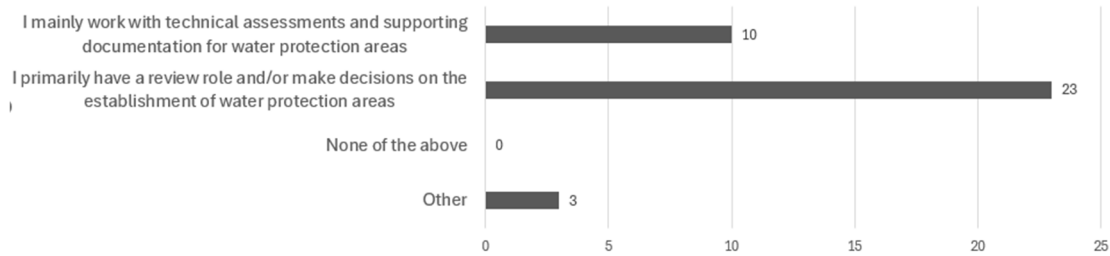
27. What is the biggest challenge you face in your work with water protection areas?

28. If you have any additional comments or feedback, please feel free to share them here:

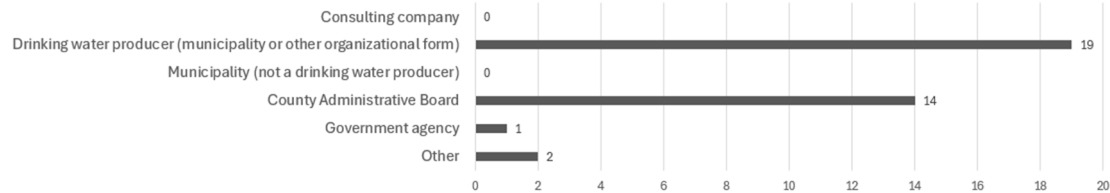
## APPENDIX B

Survey 2, directed at water resources managers in municipalities, county board administrations, government agencies, and water utilities.

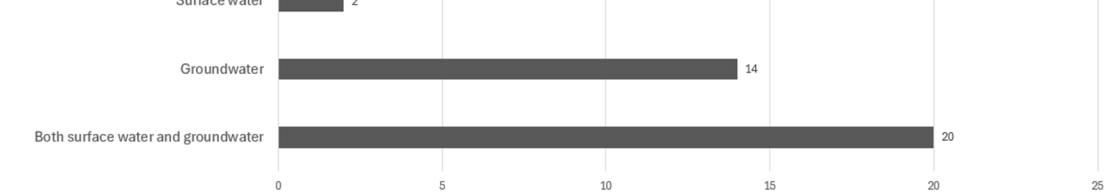
1. Which of the following roles best describes your work related to water protection areas?



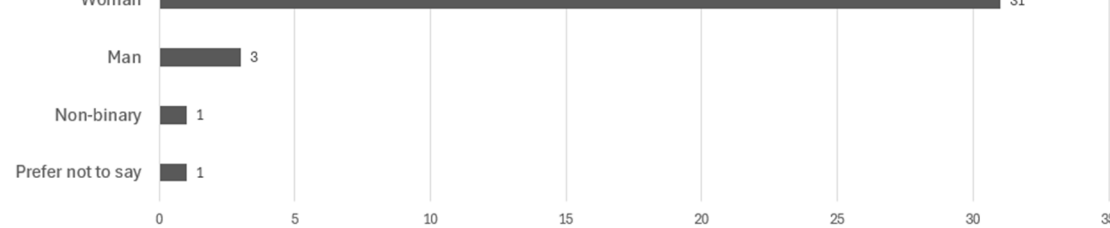
2. What type of organization do you work for?



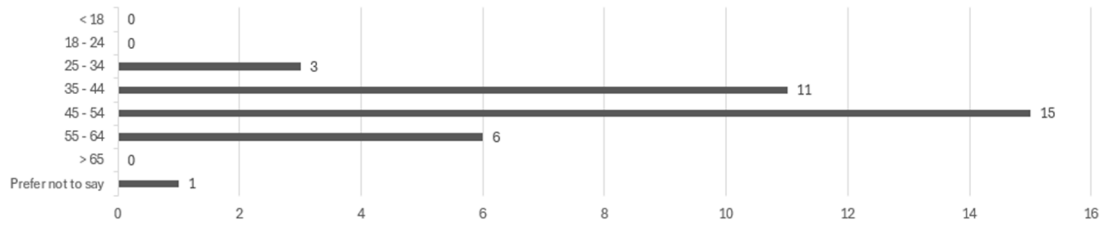
3. What type of water sources do you mainly work with?



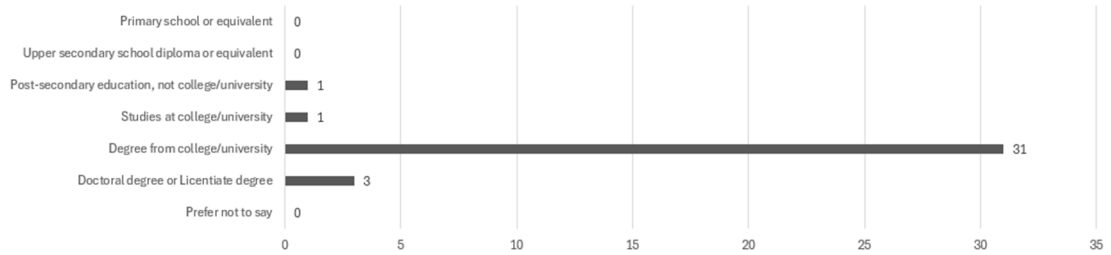
4. Which of the following best describes your gender?



5. How old are you?

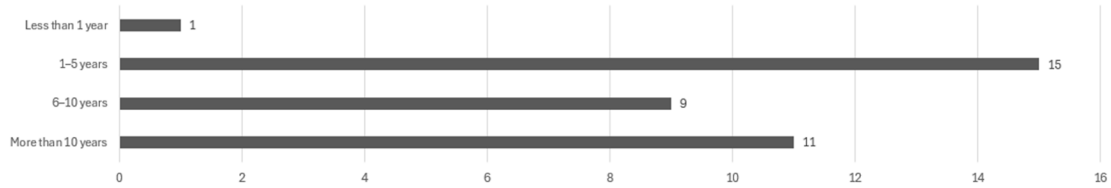


6. What is your highest completed level of education?

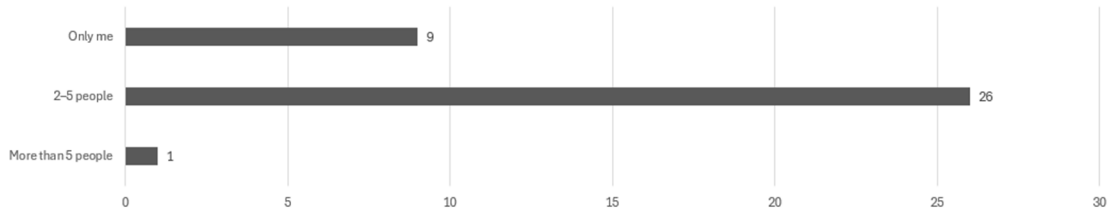


7. What is your educational field? (Please state the main subject area or discipline of your professional training or academic degree)

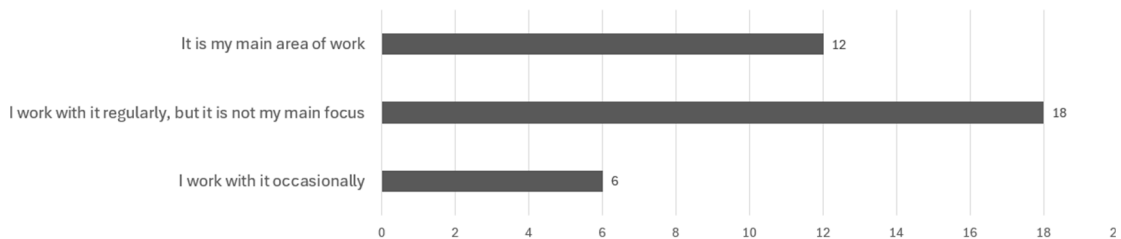
8. How long have you worked with water protection areas?



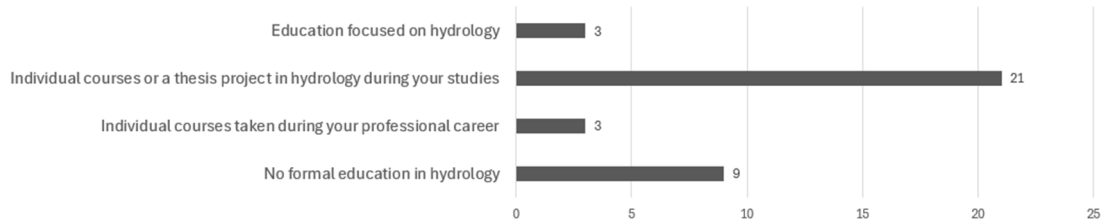
9. How many people in your organization work with water protection areas?



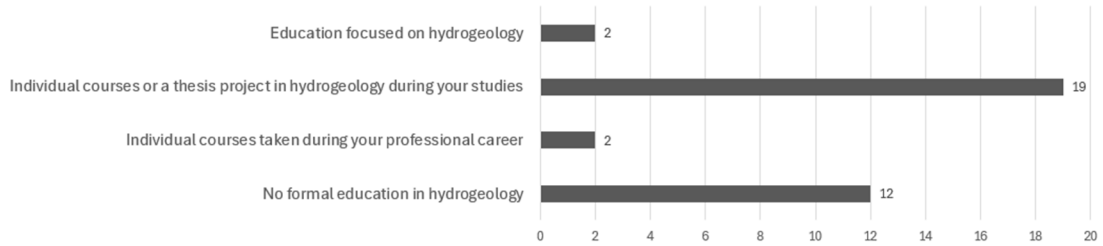
10. How would you describe your work with water protection areas (development, supervision, etc.)?



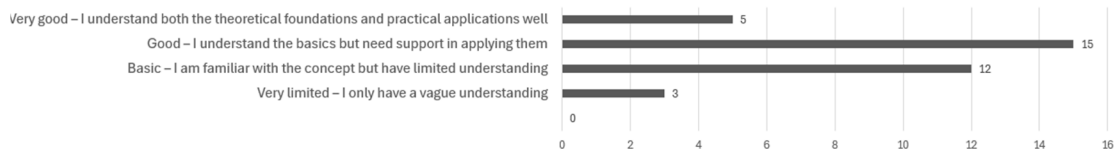
11. How would you describe your education in hydrology?



12. How would you describe your education in hydrogeology?

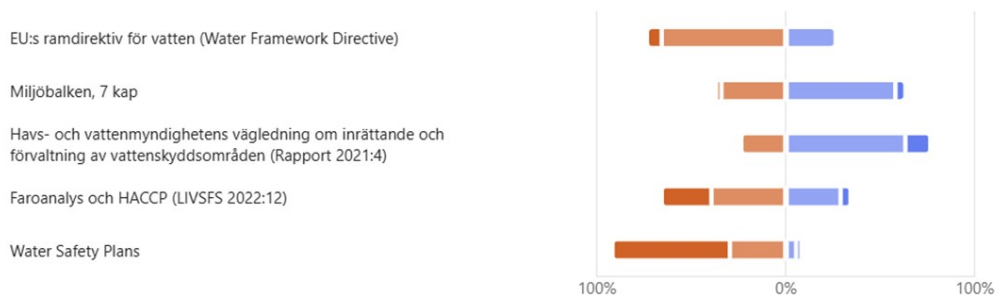


13. How would you describe your general knowledge of uncertainty analysis? (This includes understanding of how uncertainty is assessed, quantified, and managed in the risk assessment of delineating water protection areas.)



14. How familiar are you with the following guidelines, laws, or tools for working with water protection areas? (Please indicate your level of knowledge: None, Basic, Advanced, Expert)

None Basic Advanced Expert



15. Sweden now has new guidelines for how water protection areas should be established and managed. These are set out in the Swedish Agency for Marine and Water Management's guidance (Report 2021:4). The guidelines emphasize a more risk-based approach to water protection areas. To what extent do you agree with the following statements?

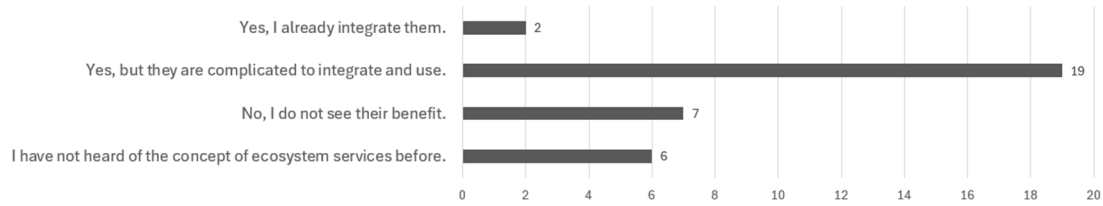
(Please indicate the degree to which you agree: Do not agree at all, Agree partly, Agree mostly, Agree completely, Do not know)

Disagree Agree partly Agree mostly Agree completely Do not know



## Appendix B

16. Do you think ecosystem services should be used in the planning of water protection areas?

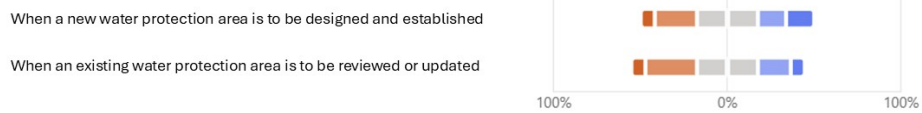


17. How would you describe your role in work related to water protection areas?

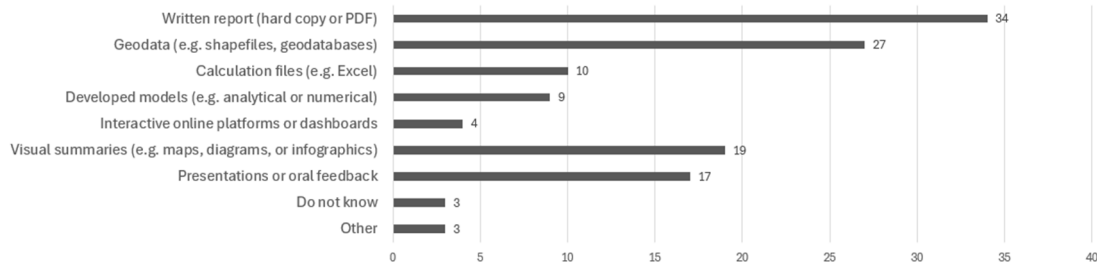
18. Briefly describe what the process of preparing and establishing a water protection area usually looks like in your organization.(e.g. assignment, drafting procurement documents, hiring a consultant, drafting agreements, reviewing reports, etc.)

19. Do you usually have enough time (and budget) to carry out the work in the way you believe it should be done in the following situations?

Always enough time   
  Usually enough time   
  Usually not enough time   
  Never enough time   
  Do not know



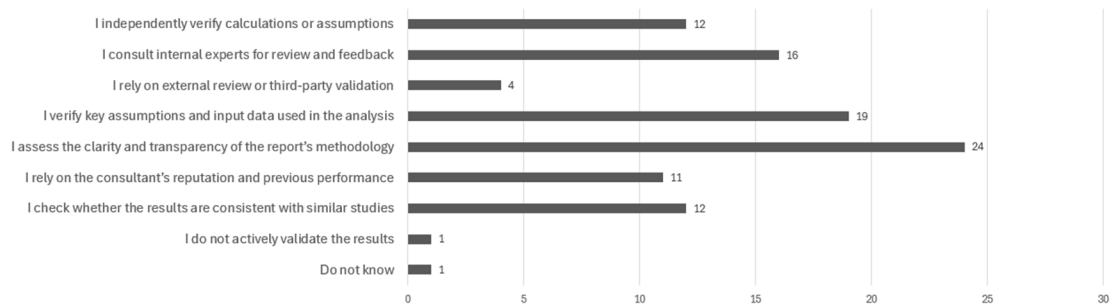
20. In what format do you prefer to receive investigations and other results used as supporting documentation for a water protection area?  
(Multiple answers possible)



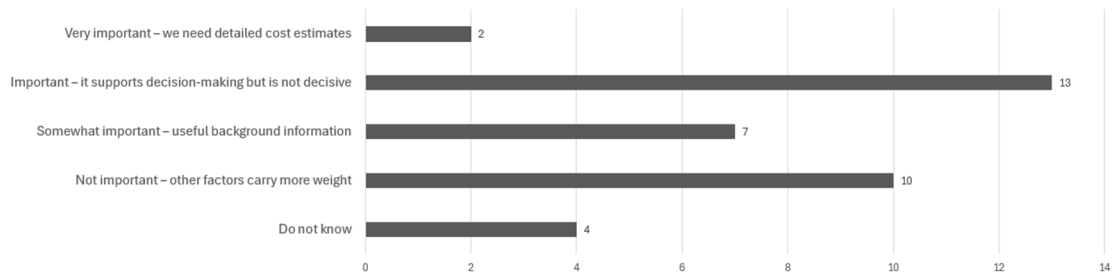
21. Which aspects are most important to you regarding results from investigations, etc. used as supporting documentation for water protection areas? Rank the options below from most to least important. (Top = Most important, Bottom = Least important)

- |   |   |
|---|---|
| 1 | Effective protection  |
| 2 | Clear recommendations   |
| 3 | Technically detailed results (including margins of error and uncertainties) |
| 4 | Results based on modeling   |
| 5 | Minimal restrictions  |

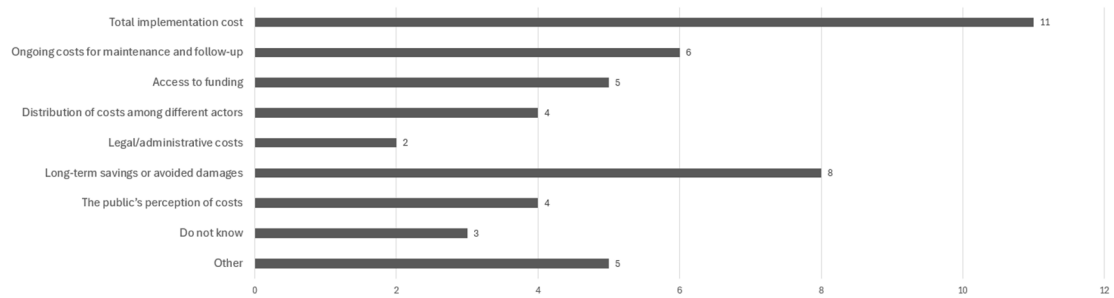
22. How do you assess the reliability of the results you receive from investigations used as supporting documentation for water protection areas?  
(Multiple answers possible)



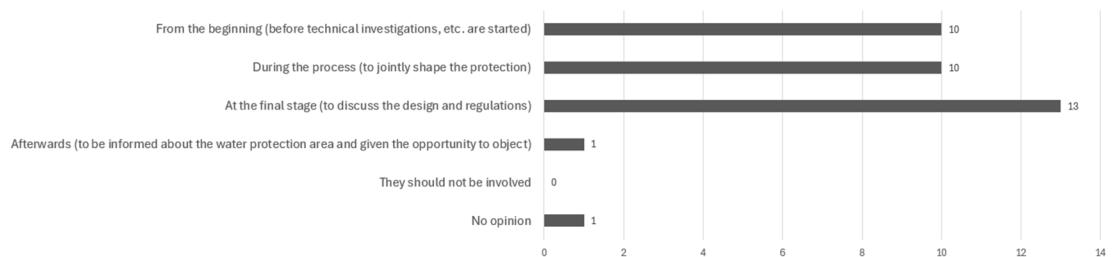
23. How important do you consider economic aspects to be in the establishment of a water protection area?



24. Which economic factors do you consider have the greatest influence on decisions about protection measures?  
(Choose up to three options)



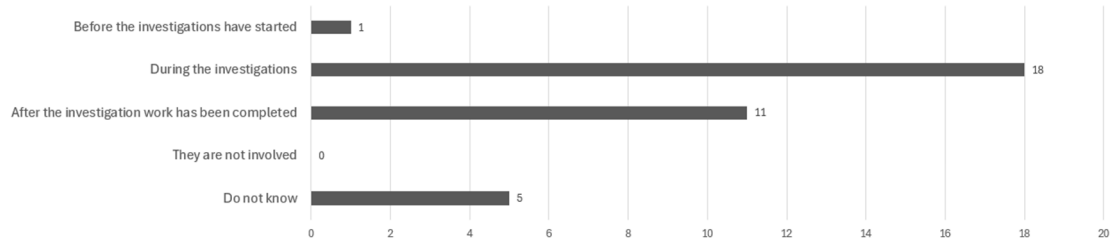
25. In your opinion, at what stage should citizens, landowners, or other stakeholders first be involved in the process of establishing a water protection area?  
(i.e. what you think is best, not what is done in practice)



## Appendix B

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26. Based on your experience, when are citizens, landowners, or other stakeholders first actually involved in the process of establishing a water protection area?



27. What is the biggest challenge you face in your work with water protection areas?

28. If you have any additional comments or feedback, please feel free to share them here: