THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Advancing the Implementation of Protective Measures for Drinking Water Sources in Sweden

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ABSTRACT

The world's drinking water sources are under growing pressure due to human activities, including infrastructure projects, agriculture, climate change, and the ever-increasing need for freshwater. Although there is a strong call to protect our source waters instead of increasing treatment efficiency at the drinking water treatment plant, the extent of protection measures is often hotly debated. A variety of challenges hinder the design and deployment of measures since their implementation is not simply a technocratic exercise but is ingrained within cultural, political, and ecological considerations. These challenges include competing interests of stakeholders, a multitude of potential hazards towards the water source, the complexity of risk assessments, the inherent uncertainty of the natural system and future conditions, and a lack of capacity and resources, especially for small drinking water systems.

The overarching aim of this thesis is to improve the implementation of water protection measures for drinking water sources in Sweden. The thesis shows how effective management of water sources can be improved by considering drinking water protection as a spatial planning problem. It illustrates how knowledge of spatial planning can be integrated with a set of theories, concepts, and methods to address some of the critical challenges affecting the implementation of water protection measures. Special attention is dedicated to the concept and methods of ecosystem services assessment, the theory of environmental justice, the methods of risk and uncertainty assessment, and the experience with the inclusion of traditional knowledge in spatial planning.

The findings indicate that the implementation of water protection measures could improve by engaging with more modern theories of spatial planning. It provides a method to comprehensively and efficiently map the many benefits that drinking water sources provide to society through the adaptation of the ecosystem services framework. Furthermore, a broader range of consequences towards water system services is accounted for with the newly developed risk assessment method improving the representativeness of the landscape complexity. Lastly, this work shows that knowledge of distributional justice could be used for the prioritization of water protection measures.

Future research will address the remaining challenges with the integration of uncertainties, quantitative risk assessments and interregional learning. The research will represent a significant step towards the effective implementation of drinking water protection measures in Sweden.

Key words: water protection, drinking water, risk assessment, spatial planning, mitigation measures, groundwater, surface water

LIST OF PUBLICATIONS

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

I. 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. https://doi.org/10.3390/w14081180

II. Gärtner N., Rosén L., Lindhe A. (2022). *Socio-economic disparities in the supply of drinking water in a Swedish region*. Manuscript

Division of work between the authors:

Paper I) Writing—original draft preparation, N.G.; writing—review and editing, N.G., A.L., L.R., T.S. and J.N.; conceptualization, N.G., A.L. and T.S.; methodology—WSS list, N.G., A.L., T.S., J.W., L.R., H.N., J.N. and L.-O.L.; methodology—risk assessment, N.G. and A.L.; software, N.G.; validation, N.G., A.L. and L.-O.L.; formal analysis, N.G.; investigation, N.G.; data curation, N.G.; visualization, N.G.; supervision, A.L.; project administration, A.L.; funding acquisition, A.L., L.R., T.S. and J.N.

Paper II) NG was responsible for the conceptualization, the methodology, the data analysis and writing of the original draft; AL assisted with the data acquisition; the discussion and conclusion with contributions from AL and LR

Other work and publications not appended to this thesis:

- Lindhe A., Gärtner N., Rosén L., Norrman J., Söderqvist T., Nordzell H., Wahtra J., Hasselström L., Lång L.-O. (2021) *Water system services as a basis for identifying costs and benefits of water protection measures* (Abstract). Presentation at the IWA World Water Congress 2021, May 24 – June 4
- Gärtner N., Lindhe A., Rosén L., Söderqvist T., Wahtra J. Söderqvist T., Wahtra J. (2021). *Using water system services to prioritize between water protection measures* (Abstract). Poster presentation at the IAH conference 2021, September 6 – 10
- Gärtner N., Lindhe A., Rosén L., Söderqvist T., Wahtra J. (2021). *Map and value services of drinking water sources* (Abstract). Presentation at the Hydrologidagarna 2021, October 6
- Gärtner N. and Lindhe A. (2022). *Not worth the effort? Benefits of integrating ecosystem services into a risk assessment for small systems* (Abstract). Presentation at the IWA Water Safety Conference in Narvik 2022, June 22 – June 24
- Gärtner N. and Lindhe A. (2022). *Socio-economic patterns of drinking water consumers in the Gothenburg region - Spatial data analysis of characteristics, and geological risks* (Abstract). Presentation at the Geological Society of America Conference in Denver 2022, October 9 – 12. *(Abstract and presentation prepared by N. Gärtner, presentation held by A. Lindhe).* https://doi.org/10.1130/abs/2022AM-382958

- Gärtner N., Lindhe A., Lång L.-O., Rosén L. (2022). *Combining Risk Assessments for Drinking Water Protection with Ecosystem Services - An Application* (Abstract). Presentation at the Grundvattendagarna in Gothenburg 2022, October 18 - 19

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1 Introduction

1.1 Motivation

Reliable access to good quality water sources is key for human development. However, the world's drinking water sources are under growing pressure due to human activities, including infrastructure projects, agriculture, climate change, and the ever-increasing need for freshwater (Mekonnen and Hoekstra, 2016). The United Nations address this issue and aim with target 6.1 of the Sustainable Development Goals (SDGs), at '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 our drinking waters (Benotti et al., 2009) and there is a strong call to protect our source waters instead of increasing treatment facilities at the drinking water treatment plant (Lubick, 2008).

Although there is a general consensus that these precious resources should be protected, the extent of protection measures is often hotly debated. The implementation of drinking water protection is not a technocratic exercise but is ingrained within cultural, political, and ecological considerations. A number of challenges hinder the design and deployment of measures to protect drinking water sources.

The populations in the Nordic countries regard their drinking water quality as reliable and safe (Bendz and Boholm, 2020), leaving little enthusiasm for further restrictions around their source waters. However, stakeholders typically underestimate the benefits of protection efforts as assessments focus only on the provision of drinking water and disregard the additional services provided by a clean drinking water source. Drinking water sources provide a wide variety of benefits, including, amongst others, using a lake for swimming, visiting a beautiful spring, watering livestock, or installing ground source heat pumps. This variety increases the complexity of the system to be managed. For an equitable accounting of protection costs versus the benefits of clean water, all services provided by a drinking water source should be considered. There is a need for assessments that allow holistic identification of costs and benefits and illustrate synergies and trade-offs of protective measures beyond drinking water protection.

The variety of potential hazards which can affect the water sources is very wide. However, often such variety is neglected to reduce the complexity of the assessment. International organizations like the World Health Organization (WHO, 2017a), the EU's Drinking Water Directive (EC, 2020) and national organizations such as the Swedish Agency for Marine and Water Management (SwAM, 2021) stress the importance of risk-based approaches to account for potential hazards towards a drinking water source. In the near future, water utilities will therefore have to work even more with source water protection and specifically adapt a risk-based approach.

Restrictions introduced for protecting drinking water sources are often appealed by affected stakeholders who believe the risk assessment of the water source is inaccurate. While underprotection may harm the water source, leading to the contamination of a vital resource, overprotection unnecessarily restricts social and economic activities. However, protective measures are inherently uncertain due to the geology and natural conditions of the water sources. Even though there are many methods to decide on the extent of watersheds, there is no 100% certainty for their results. Since the implementation of water protection measures has wide-reaching impacts, new methods should account for uncertainty when assessing restrictions.

Effective management of drinking water sources requires capacity and resources. Often these are lacking, especially in the context of small drinking water supplies in developing as well as developed countries (Gunnarsdottir et al., 2017). Small drinking water supplies contribute significantly to water-borne disease outbreaks in the Nordic countries (Herrador et al., 2016) but can only count on little financial, technological, and personnel resources. There is growing attention to the need to improve the management of this type of water supply, also learning from experiences outside the Nordic countries.

1.2 Aims and Objectives

The overall aim of this thesis is to *improve the implementation of water protection measures for drinking water sources in Sweden*.

In this thesis, I show how effective management of water sources can be improved by considering drinking water protection (DWP) as a spatial planning problem. The thesis shows how knowledge of spatial planning can be integrated with a set of theories, concepts, and methods to address the challenges identified in section 1.1. Of special attention are the concept and methods of ecosystem services assessment, the theory of environmental justice, the methods of risk and uncertainty assessment, and the experience with the inclusion of traditional knowledge in spatial planning.

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

- Learn from the theory and practice of spatial planning to guide the development of new approaches for water protection measures.
- Develop a method to comprehensively and efficiently map the many benefits drinking water sources provide to society through the application of methods for Ecosystem Services assessment.
- Expand the scope of conventional risk assessments for drinking water sources to acknowledge the variety of benefits they may provide to society.
- Explore ways of analysing differences in society with respect to access to drinking water sources and drinking water.

1.3 Thesis Structure

The licentiate thesis contains nine chapters which explore the challenges of implementing water protection measures and investigate potential solutions (see Figure 1).

CHALLENGES	1. Introduction 2. Key Concepts 3. Historic and Current State of Drinking Water Protection 4. Drinking Water Protection as a Spatial Planning Problem	Theoretical background (What made this research necessary?)
SOLUTIONS	5. Dealing with the Challenges of Water Protection Measures as a Spatial Planning Exercise	Identified concepts guiding solutions
	6. Papers 7. Discussion	Application of the solutions
	8. Where To From Here	Outlook
	9. Concluding Remarks	

Figure 1. Structure of this licentiate thesis

The first part of the thesis explores the challenges that arise when water protection measures are implemented. The first chapter introduces the licentiate including its motivations, aim and objectives. Chapter 2 defines key concepts such as hazards, vulnerability, risk, and uncertainty that are necessary to understand the problems associated with drinking water protection. Chapter 3 outlines the development of water protection measures from practices of 4000 years ago to today's guidelines and legislation. Finally, chapter 4 contextualises the challenges of drinking water protection in the spatial planning sphere.

The second part, comprising chapters 5 to 8, offers possible solutions to some of the challenges of implementing measures for drinking water protection. Chapter 5 presents identified concepts that could guide potential solutions, and chapter 6 relates those concepts to water protection measures and applies them to case studies. Chapter 7 discusses the main contributions of the research and evaluates potential obstacles in their application. In chapter 8, future studies are outlined.

Finally, some concluding remarks are presented in chapter 9.

2 Key Concepts

Drinking water sources are under constant pressure from natural and anthropogenic activities. For a water source to be exposed to a risk, a stressor (the hazard) must be present, and at the same time the drinking water source must be vulnerable to the potential contamination or other effects that the hazard may cause. Only then does the stressor pose a risk to the drinking water source (see Figure 2). In this chapter, hazard, vulnerability, risk, and uncertainty are presented since they are key concepts necessary to understand and describe the work presented in this thesis.

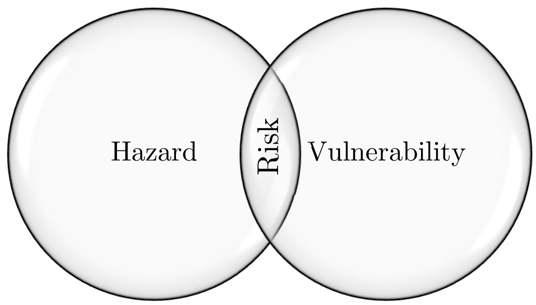


Figure 2. Illustration of the interplay of hazard, vulnerability, and risk towards a drinking water source

2.1 Hazard

Rausand (2011) defines hazard as *a source of danger that may cause harm to an asset.* In the case of drinking water sources, a hazard can concern the quality or the available quantity of source water.

A hazard concerning quality is a prerequisite that the water source becomes contaminated and may pose a danger to humans when the water is used for human consumption. Drinking water hazards regarding quality can be sorted into chemical, microbial, physical, and radiological hazards (WHO Europe, 2019). A hazard or hazard source can refer to an ongoing activity or a specific circumstance, whereas a hazardous event typically describes the event causing a contamination or another effect on the water supply. Furthermore, the specific contaminants are typically referred to as hazardous agents.

Chemical hazards can be naturally occurring, such as arsenic in a groundwater source, or they may originate from anthropogenic sources due to industrial or agricultural activities. Microbial hazards are pathogens transmitted via drinking water, primarily of faecal origin (Ashbolt, 2004), including bacteria, viruses and protozoa. Common pathogens comprise norovirus, rotavirus, giardia, shigella, helicobacter, salmonella, and cryptosporidium. Ashbolt (2004) provides an overview of the most common water-borne pathogens of concern and lists the main diseases they are causing and their primary sources. Physical hazards impact the physical appearance or properties of water, including sedimentation and metals, plastic or stones in suspension (Tsitsifli and Kanakoudis, 2020). Radiological hazards can be of natural origins, such as radon contamination from this naturally occurring radioactive gas formed by the decay of uranium and thorium in igneous rocks and soils. Spills and leakages of radioactive materials in mines, landfills and industrial sites can expose the drinking water source to radiological hazards of anthropogenic origin.

2.2 Vulnerability

Vulnerability represents a water source's natural characteristics that determine the ease with which the source water may be contaminated or unavailable. For example, if there are pathways from the hazard source to the water source, it is considered vulnerable, but there might be a natural barrier making the water source less vulnerable.

Machiwal et al., (2018) define two types of vulnerability: intrinsic and specific vulnerability. Intrinsic vulnerability considers the physical characteristics of the water source but is independent of the type of contaminant. On the other hand, specific vulnerability describes the vulnerability of the water source to a certain contaminant. It includes the transport characteristics due to the components of intrinsic vulnerability while simultaneously acknowledging contaminant characteristics and attenuation processes.

2.3 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). They describe risk *as an event that may occur and cause harm to a system we aim to protect*. Quantitatively, the risk for each event i is hereby expressed as a set of triplets, including the scenario identification s_i, the probability p_i of that scenario to happen, and the consequence c_i if that scenario happens. To be able to define those triplets, the risk analysis has to answer the following questions:

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

Protection efforts regarding drinking water fit very well this definition of Kaplan and Garrick. I, therefore, build on Kaplan's and Garrick's definition and define the risk (R) posed by a hazard (i) on a drinking water source as a function

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

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.

2.4 Uncertainty

Hubbard (2014) defines *uncertainty* as the lack of complete certainty, i.e., that more than one possibility exists in which the one true result is not known. In the field of water management, understanding the uncertainties is crucial when quantifying risks towards a drinking water source. Furthermore, uncertainties are of key importance when assessing risks since a lack of data is common, and future conditions may not be fully known.

In this thesis, two types of uncertainties are important to be looked at. First, there is parameter uncertainty indicating that there are several unknown model parameters. This type of uncertainty is often addressed by assigning probability density functions (PDF) to a specific parameter instead of only using a deterministic value for the said parameter.

Second, there is model uncertainty. In the case of drinking water sources, model uncertainty often refers to the suitability of a chosen model to represent the environmental conditions correctly.

There is also aleatory and epistemic uncertainty which may contribute to both parameter and model uncertainty. Bedford and Cooke (2002) define these two concepts as the following. *Aleatory uncertainty* is due to the inherent or natural variability and cannot be reduced by measurements or studies. *Epistemic uncertainty* refers to the lack of knowledge and can be reduced by measurements giving us less uncertainty about model parameters (e.g., mean values) or the choice of appropriate models.

3 Historic and Current State of Drinking Water Protection

Throughout history, societies have understood the importance of protecting drinking water sources without understanding the science behind them, and people implemented protection measures. This chapter provides an overview of the development of water protection measures from ancient practices to conventional methods and modern guidelines and legislation.

3.1 Historical Development of Drinking Water Protection

Since humans settled into cities and the first early civilisations developed, settlers started to deliver water from the source into the city walls. The delivery of safe water is seen as one of the main drivers for forming states, and this collaborative activity helped bind communities together (Manuel et al., 2018). However, not only the delivery of water and the corresponding technical executions were regulated to ensure water delivery and avoid contamination, but also the water source enjoyed special protection.

The first manufactured constructions of subsurface water channels are called "qanats" and were developed 6000 years ago in today Iran. They are subterranean tunnels dug to transport the water from the uplands to the plains. These channels are excavated from the plains towards the water source, the so-called mother well (Manuel et al., 2018). An essential step in constructing the qanat is identifying an appropriate water source where sufficient flow and adequate water quality are ensured. These installations came with an institutional framework for water management which dates to the era of the Babylonian King Hammurabi around 2000 BC (Gholikandi et al., 2013). This code of law specifies water protection measures such as safeguarding surface sections on top of the qanat by the landowner, which prevents contamination, liability for damage due to negligence or malice and accepting community rules (Gholikandi et al., 2013). No specific measurements for water protection areas are mentioned, but the idea of protecting the source water along its way was implemented.

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*) in the first place among the common goods that all humans share (Bannon, 2017). One of the most famous Roman constructions in water technologies are aqueducts, a watercourse that carries water mainly on the surface from the source to its destination. During Roman times, aqueducts and water facilities were protected by law, and specific protection measures were laid out. In order to protect the transported water against contamination, specific buffer zones between private properties and the aqueduct were enforced. In these buffer zones, it was not allowed to plant trees or build (10 feet to each side of the structure)(Frontinus, 100AD).

In contrast to the water management in ancient Iran, the water source itself enjoyed special protection in the Roman Empire. In the report *De aquaeductu* (*engl. on aqueducts)* written by the Roman engineer and water commissioner Sextus Julius Frontinus, a circular water protection area must be assigned around water sources, and prohibited activities in its immediate vicinity are listed. For example, around the springs, a protection zone of 4.5 m was assigned, and it was forbidden to construct, establish a place, plough in and sow, or introduce anything into that area. Furthermore, it was strictly forbidden to graze livestock, cut hay, grass, or remove brush, and the natural vegetation layer should not be removed. A fine would be collected and distributed equally to the accuser and the state treasury if the statutes were not followed. 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, a regression started, and source water protection measures fell into oblivion. Water sources were still a common good but depleted due to the inhabitants' way of life (Ewert, 2007).

In the 19th century, the understanding that pathogens are causing water-borne illnesses in source waters and that these pathogens can be mitigated by improved water management (re)entered the scientific discourse. For example, in 1855, Dr John Snow was the first epidemiologist to connect a cholera outbreak in London to a sewage-contaminated well (US-EPA, 1999).

In modern times, the United States of America and Germany were pioneers in protecting and developing guidelines and legislations for groundwater protection areas (Doveri et al., 2016). The Federal Water Pollution Control Act of 1948 was the first major U.S. law to address water pollution (US-EPA, 2021). In 1974, the Safe Drinking Water Act became effective and ensured safe drinking water for the public. In 1986, the Wellhead Protection Program was amended to the Safe Drinking Water Act, which obliges states to protect underground drinking water from contaminants that might harm human health. In Germany, the Federal Water Act was adopted in 1957 and regulated the discharge of pollutants into the groundwater.

Apart from the unintentional contamination of water sources, source water has often been subject to ill-intentioned handling from ancient times on and was even used as a weapon in conflicts. 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 hurled decomposing human bodies into the enemy's water wells (Lindeke, 2018). Since the 20th century, the knowledge about harmful substances to our source waters has been extensive and openly available, and with it, the constant threat of calculated source water contamination. This threat provides additional motives to protect source waters from biological and chemical warfare and stresses the necessity to assign adequate protection areas and measures. Nowadays, many source water protection plans try to include measures to protect from sabotage and terroristic attacks.

3.2 Traditional Approach to the Protection of Drinking Water Sources – Delineation

The main aim of delineating a water protection area was traditionally to protect the source water against microbial and chemical contamination threats. The zonation of water protection areas is generally based on an (advective) travel-time analysis of the water (Enzenhoefer et al., 2014). Travel times offer the responsible operators the adequate time to ensure a measure to react to a contaminant spill and take remedial action or that the assigned travel times provide an appropriate time frame for the pollutants of interest to decline to an acceptable level before reaching the abstraction point (Chin and Asce, 2018). In order to implement adequate protection measures, the protection zone is often split into subzones with different tiered protection levels and decreasing restrictions parting from the abstraction zone.

3.2.1 Delineation Methods for Groundwater Sources

The catchment basin is typically divided into different zones: the well-head protection area, and a primary, secondary, and sometimes tertiary protection zone (see Figure 3). The well-head protection area is the zone closest to the well. The close area around the well-head is usually protected with a fence against trespassing, and all activities are prohibited. The primary protection zone describes the area where the groundwater will reach the well within a predetermined number of days. It is established to ensure enough time to react upon potential chemical contamination or to immobilize microbiological contamination of the well. The secondary protection zone recommends an extent of travel time from the outer rim of the secondary zone to the production well-area. This is to guarantee sufficient time to act but also that somewhat more hazardous activities can be allowed. The tertiary protection zone might cover the remaining extent of the contributing recharge area.

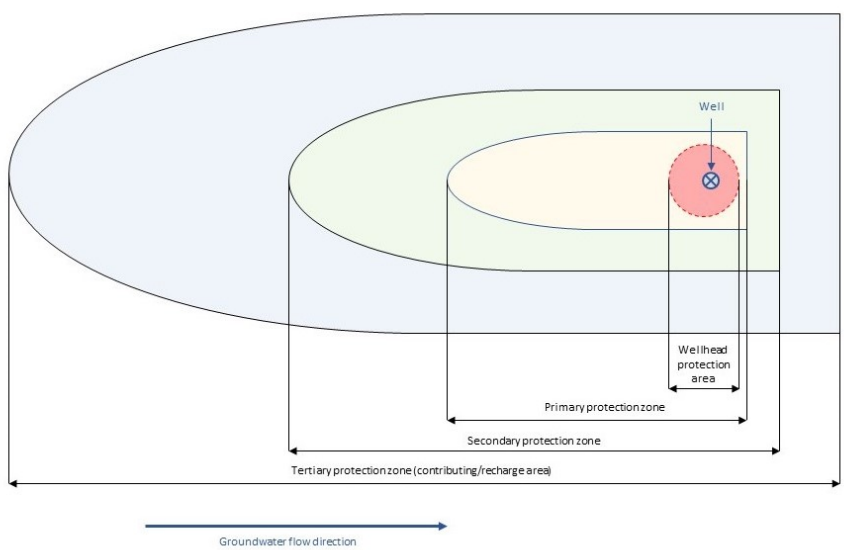


Figure 3. Theoretical wellhead protection zones

The traditional delineation methods are classified into five groups (US-EPA, 1987), from easily performable and therefore economic (fixed radius method) to increasing complexity and more costly (numerical models). The methods are named and described in Table 1.

Table 1. Delineation methods for groundwater sources

Method	Description
Fix radius method (arbitrary fixed radius)	– Protection area is a circle around the well – Discharge rate is often the only considered parameter when choosing the distance
Fix radius method (calculated fixed radius)	– Protection area is a circle around the well – Circle's radius is calculated based on specific time-of-travel criteria (critical time for a contaminant to reach the well)
Simplified variable shapes	– A set of various standardized forms are generated beforehand by experts using uniform flow equations – 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 – The shape represents the delineation of the water protection area
Analytical methods	– Equations describe the groundwater flow and contaminant transport for specific conditions – Main steps are to identify the distance to the downgradient and the distance to the upgradient
Hydrogeologic mapping methods	– Experts identify the flow boundaries with the aid of maps – The geological boundaries correspond to the water protection area
Numerical flow/transport models	– Use of software (computer models) to solve the groundwater flow equations and particle transport equations numerically

The handbook about water protection areas used in Sweden until 2021 (SEPA, 2011) provides guidelines for delineating water protection areas. An overview can be found in Table 2 (the new handbook is presented in section 3.3.3). The catchment basin is divided into four zones: the well-head protection area, and the primary, secondary, and tertiary protection zones (SEPA, 2011). The well-head protection area is the zone closest to the well. The close area around the well-head is usually protected with a fence against trespassing, and all activities are prohibited. The primary protection zone describes the area where the groundwater will reach the well within 100 days. It is established to ensure enough time to react upon potential chemical contamination or to immobilize microbiological contamination of the well. The secondary protection zone recommends an extent of travel time (TOT) of one year from the outer rim of the secondary zone to the production well-area. The tertiary protection zone covers the remaining extent of the contributing recharge area.

Table 2. Example showing how well-head protection zoning can be defined in Sweden

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

3.2.2 Delineation Methods for Surface Water Sources

Similar to the groundwater sources, the catchment basin is typically divided into different protection zones: the area around the intake, a primary, secondary, and tertiary protection zone (see Figure 4).

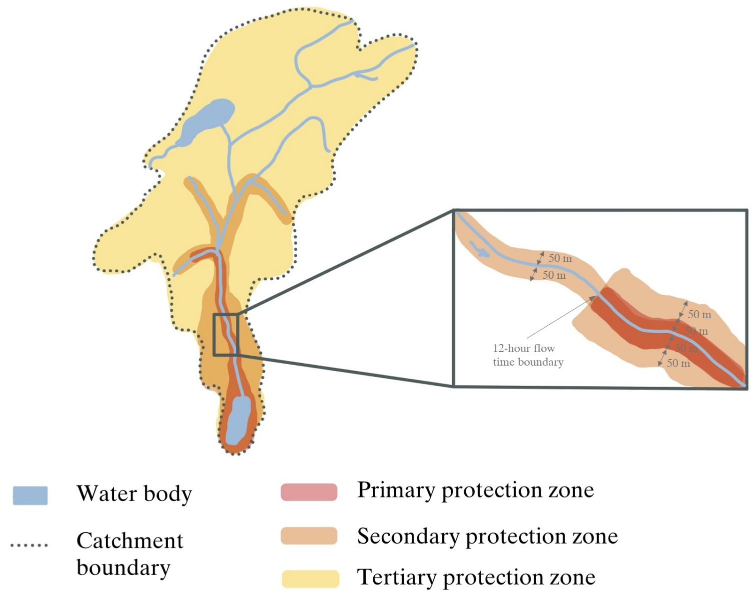


Figure 4. Delineations of surface waters. The illustration on the left illustrates the three protection areas. The illustration on the right shows the two beach zones (modified after SEPA, 2011).

The US-EPA (2006) provides an overview of the different delineation methods available for surface water sources. A detailed description of delineation methods is given in Table 3.

Table 3. Delineation methods for surface water sources

Method	Description
Arbitrary distances	– Protection area is a circle around the intake – Radius of the area is not based on the surface water body's hydrology
Entire watershed or hydrologic unit containing the intake	– Protection area contains the entire watershed with the complete contributing area or the hydrologic unit containing the intake – Protection area can be adopted from pre-elaborated maps that contain the delineated watershed. Or it can be delineated with a watershed delineation software such as HEC-GeoHMS (Fleming and Doan, 2009)
Stream time-of-travel distances upstream of the intake	– Protection area corresponds to the length of the stream above the intake, through which this water unit will travel during a defined travel time criterion (critical time for a contaminant to reach the intake)
Buffer zones	– Protection area comprises areas along the stream banks. A minimum width is chosen and perpendicularly assigned to the stream for the length calculated with the time-of-travel criterion
Time-of-travel area including overland flow	– The area includes everything that could potentially drain within a beforehand defined time (critical time for a contaminant to reach the intake) including the travel time of the overland flow

The former Swedish handbook (SEPA, 2011) provides guidance on the extent of the protection zones. A water intake zone should be defined around the raw water intake in the river or lake. The area should be protected against unauthorized access and should only be managed by the responsible water entity. Activities other than water withdrawal should not occur within this area.

Table 4 summarizes the details on water protection zoning for surface water sources in Sweden. The primary protection zone for an intake in a surface water body is determined by the flow time of twelve hours (SEPA, 2011). The Swedish EPA recommends that the dimensioning flow time for the primary zone for lakes and watercourses should refer to a high flow situation with a return period of at least 10 years. The width of the coastal buffer zone corresponds to the residence time in soil and groundwater of 100 days and should be at least 50 m wide. The secondary protection zone is determined equally to the primary protection zone and is defined by a time of travel of 24 hours and an additional minimum of 50 m to the primary protection zone's buffer zone. The tertiary protection zone covers the remaining area in the watershed that is not included in the other protection zones, consisting of the area between the outer boundary of the secondary zone and the boundary of the watershed. The tertiary zone takes into account potential long-term pollution.

Table 4. Details of the water protection zoning for surface water sources in Sweden

Water Protection Area				
(Zone around intake)	Zone I	Zone II	Zone III	Reference
Not specified	12 hours, min. 50m of buffer zone	24 hours, min. 50m to zone 1 (i.e., 100m in total)	Remaining of the watershed	(SEPA, 2011)

3.3 Regulations and Guidelines for Drinking Water Protection

From the global to the national level, recent regulations and guidelines on drinking water protection push for the inclusion of risk assessments. There is a trend towards comprehensive risk-based assessments in drinking water protection where all hazards are considered.

3.3.1 WHO's Water Safety Plans

The World Health Organization (WHO) suggest the development of Water Safety Plans (WSPs) to ensure a safe drinking water supply (WHO, 2022, 2017b, 2010). Those plans encompass a proactive and comprehensive risk assessment and management in which all hazards towards a water source are mapped, and the potential risk and risk reduction through protective measures are estimated to provide comprehensive decision support (see Figure 5).

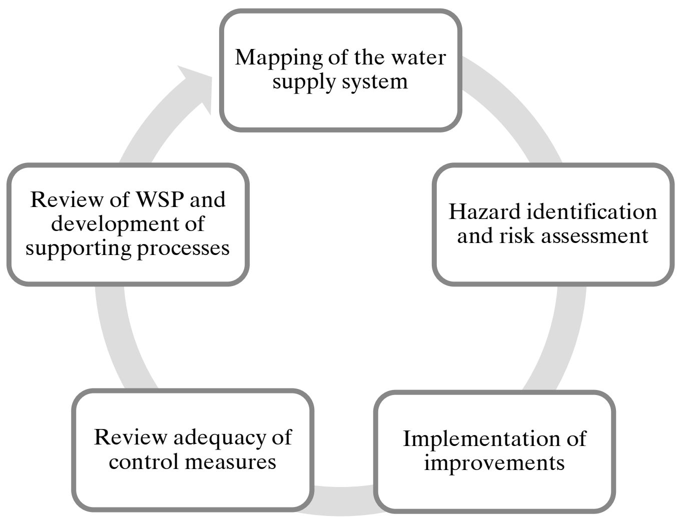


Figure 5: Implementation cycle of a water safety plan after (after WHO, 2010)

However, the WHO does not provide detailed guidance on how to delimitate and design measures for protecting water sources since the WSP is an approach looking at the entire system (from source to tap) and typically with a focus on critical control points. The concept of HACCP (short for *hazard analysis and critical control points*) is used as a basis for WSP. HACCP is a methodical preventive approach for identifying hazards and installing measures to control for them (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). 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.

3.3.2 The European Union's Directives

Two EU directives are important for the implementation of protection measures for source waters. One is the Drinking Water Directive (DWD) which focuses on the end-product (delivered drinking water) and its effects on human health (EC, 2020). The second directive is the Water Framework Directive (WFD) which centres around the status and quality of freshwater sources (which may or may not be used for drinking water) and their effect on environmental health (EC, 2000).

The Drinking Water Directive

On January 12, 2021, the revised Drinking Water Directive became effective, and all member states were given two years to adopt it into their national legislation. One of the main features of the revised DWD is the *preventive approach* which aims at reducing pollution at the source introducing a risk-based approach based on a comprehensive analysis of the entire water cycle.

Another feature worth noticing is the introduction of new water quality standards that are stricter than the WHO's recommendations, and the focus on tackling emerging pollutants such as microplastics, PFA's and endocrine disrupters.

The Water Framework Directive

While the Drinking Water Directive focuses on protecting human health, also aquatic plants and animals need cleaner water to prosper. The WFD focuses on protecting the total environment and aims to achieve good chemical status for all water bodies in Europe avoiding pollution in the first place. Considering that even small amounts of hazardous substances may harm the environment the directive establishes limit values even stricter than those of the DWD, under the assumption that water used for drinking can be treated before consumption.

3.3.3 The Swedish Handbook on Source Water Protection

The most important national reference on source water protection is the guidelines on implementation of water protection areas provided by the Swedish Agency for Marine and Water Management (SwAM), here referred to as the *Handbook on source water protection areas* (SwAM, 2021).

According to the Swedish Environmental Code c. 7 21 § (SFS 1998:808), a land or water area can be declared a water protection with the aim to protect a current or potential future drinking water source. The overall aim is to ensure a good water quality and availability to enable a safe supply of drinking water. An area is declared a water protection are by a county administrative board or municipality. Furthermore, the implementation of a water protection also includes regulations (Environmental Code 7 c. 22 §) that may restrict the land use and other activities in order to safeguard the water source.

In 2021, SwAM published this new handbook (SwAM, 2021) which completely replaces the old handbook (SEPA, 2011). Following the WHO approach, the new handbook states that water protection measures should be implemented based on risks. Hence, it is emphasised that a risk-based approach should be used both when delineating the water protection area and when establishing proper restrictions on land use. Hazard sources falling into the catchment area should be assessed based on their risk and managed accordingly. Compared to the old handbook, the new handbook does not provide any detailed calculation criteria or indicates how to delineate water protection areas. In contrast, the old handbook provided strict guidelines on delineation options based on travel times (see 3.2.1 and 3.2.2).

The old handbook was closely linked to the general guidance on implementation of water protection areas provided by SEPA (Naturvårdsverkets allmänna råd 2003:16 om vattenskyddsområden). The guidance document included advice on levels of restrictions related to different types of land use. The document was reviewed by SwAM and it was concluded that parts of it should be updated to be in line with related legislation (SwAM, 2014). In 2020, the general guidance was cancelled and replaced with the guidance provided by the new handbook.

The risk-based approach emphasised in the new handbook is used to stress that a water protection area must be tailored based on the site-specific conditions. It has been discussed that the old approach was based on too rigid delineation criteria, which led to scattered protection areas. Such scattered areas can be challenging to implement and to communicate to stakeholders. In the new handbook, it is stressed that a water protection area is one of the instruments used to protect a water source, but there are also other legislations and regulations that aim to protects water sources in different ways.

It has to be stressed that the *Swedish Handbook on Source Water Protection* is only a guideline and does not represent a legal instrument. The state does not have the mandate to enforce the use of this handbook. However, in practice, if a new water protection area is to be implemented, it should follow those guidelines. When declaring a water protection area, the county administration board or the municipality will examine if the suggested water protection measures, including the water protection areas, follow those guidelines.

4 Drinking Water Protection as a Spatial Planning Problem

Water protection measures (WPM) are not stand-alone figures in the landscape, detached from the rest of the space. Their implementation shapes the surrounding area by imposing restrictions and limitations on users and inhabitants. Due to the broad variety of impacts generated by WPM, a multitude of interests is affected in the process. The existence of competing economic interests, recreational activities, and other environmental protection goals complicates the design and implementation of WPM. Here I suggest that considering the design and implementation of WPM part of the spatial planning process of the area opens opportunities to address some of the challenges that hinder effective implementation. In this section, I provide a review of relevant (theoretical and practical) knowledge from the literature of spatial planning. Reflections on water protection measures in the light of spatial planning are presented in section 4.3.

4.1 Background on Spatial Planning

4.1.1 On the Notions of Space, Planning and Spatial Planning

When discussing spatial planning, the two concepts of space and planning should first be examined separately to find a suitable limitation of the topic.

One can think about space in several ways. There are various philosophical theories about general notions and relations of space, including famous concepts from Leibniz, Newton, Mach and many more. When focusing on a geographical notion of space, Harvey (2009) partitions the notions of space into three understandings. Space can be seen as absolute, a thing that exists independent of its matter. Alternatively, it might be regarded as relative, where it only exists because objects are present and relate to each other. Harvey (2009) describes an own third categorisation as relational space-space, where an object exists only when it contains and interacts with other objects. There are no concrete answers to those philosophical categorisations of space as the notion is defined through human practice.

Sulmicki (1974) describes planning as a set of activities of an authority that involves deciding what, how much, how, where and for whom it should be created.

Spatial planning can be regarded as any effort to control the use of land. It mediates the claims on space between the state, the market, and the community (Ziafati Bafarasat, 2015). More specifically, von Haaren et al. (2016) defines spatial planning as *the methods used by the public sector to influence the distribution of people and activities in spaces at various scales as well as the location of the various infrastructures, recreation and nature areas*.

4.1.2 The Theories of Modern Spatial Planning

During the Industrial Revolution, cities started to develop disorderedly, and there was a growing need for a structured approach to planning the urban landscape. Modern urban planning started as a response to the problems of insufficient water supply, the lack of sanitation and air pollution (Verbeek, 2014) and planners tried to provide the city's working poor with healthier environments. There are a variety of planning models, and each approach is based on a different value system (see Figure 6).

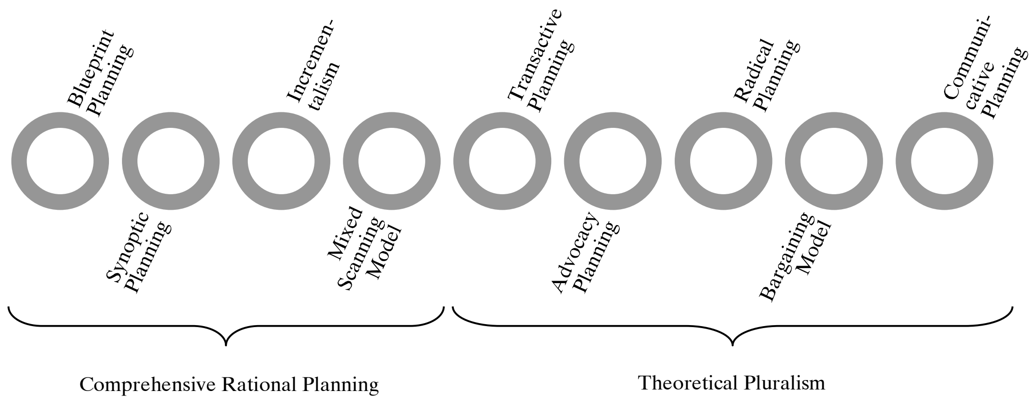


Figure 6. Spatial planning models in chronologically ascending order from left to right

The *Blueprint Approach* marks the first attempt at systematised planning. It represents a standard top-down method in which a planning entity works through an entire program towards the previously established objectives (Davidoff and Reiner, 1973). The developers decide by themselves and act as a technical elite who do not allow the public to participate in the process. Furthermore, it is assumed that there is just one single, unified public interest and that the planning itself is apolitical (Lane, 2005). Blueprint planning was defeated in the 1960s (Lane, 2005) due to its detachment from the public will, which ended in the demolition of projects and the civic rejection of renewal projects.

Synoptic Planning evolved with the downfall of the blueprint approach and can be seen as an extension of the rational paradigm. This planning model specifically emphasises the goals and targets, quantitative analysis and a prediction of the environment, the evaluation of alternative policy options and the evaluation of means against ends (Lane, 2005). However, this planning approach still sees society as a homogenous entity where the goals are universally shared. Starting from that assumption, public participation is just another way to approve the planning goals and legitimise the planning activities (Kiernan, 1983). The main fallacy lies in the planner's expectation that the future will evolve and develop as foreseen.

Incrementalism is a planning technique where small changes are gradually implemented, and change increases progressively. The synoptic planning and the blueprint approach were marked as impractical, and it was sought after a more realistic guide to decision-making. Incrementalism (sometimes also referred to as "muddling through") means selecting alternatives and their respective consequences that only differ incrementally from existing policies. Furthermore, incrementalism includes constantly adjusting the objectives and continuously evaluating and analysing the data and outcome (Lane, 2005). This approach acknowledges more than one common interest and admits a plurality of concerns.

The *Mixed Scanning Model* was first published by Etzioni (1967) and sought to overcome the central problems of the before-mentioned planning approaches. Those models were still based on a unitary public-interest model and the planner's central figure in the planning process. This method tries to manage the data overload and focuses on the short-term (tactical) and long-term (strategic) needs of the planning and can be exemplified as "better having a good plan today than a perfect plan tomorrow". The mixed scanning approach stands for a variation of the inflexible synoptic planning approach (Etzioni, 1967; Lane, 2005) and leaves room to explore innovative solutions that might diverge strongly from the status quo instead of the conservative incremental approach. In addition, it was novel that comments from the public were included in the planning process. For the first time, stakeholders outside the planning arena were allowed to participate partially in the planning process.

Social transformations set the ground for a break in planning traditions. Until then, the planning models have been top-down models with a strong focus on the planner and the planning institutions, but societal change paved the way for bottom-up approaches.

Friedman developed *Transactive Planning* in 1973 due to the shortcomings of the comprehensive rational planning methods (Lane, 2005). This new planning technique is based on face-to-face interaction and interpersonal dialogue with stakeholders, leading to intensive communication about possible measures. People affected by the decisions should have direct contact with the planner. The planning itself is less data-oriented but relies heavily on interpersonal dialogue (Hudson et al., 1979). Planners hold technical knowledge and can take on the role of mediators. They intercede between diverse interest groups and try to reach an agreement between the different parties.

Advocacy Planning was first presented by (Davidoff, 1965). This theory exclusively sides with the stakeholders who lack the means and skills to progress their interests and ensures that the interests of the weak are defended against the interests of the strong (Hudson et al., 1979; Kinyashi, 2006; Lane, 2005). This planning approach roots in the legal profession and court cases (Hudson et al., 1979), where planners should inform disadvantaged groups about their rights and information and represent them as a legal defendant would do. The planner warrants that otherwise unheard interests are accommodated in decision-making (Lane, 2005).

Radical Planning, sometimes referred to as Marxist Approaches to Planning, assumes that the capitalist system oppresses some social groups. The state is seen as a collaborator of the capital, and planning is an instrument that guarantees the accumulation of capital (Lane, 2005). Following this planning theory, the planner's role involves helping the oppressed groups by organising and cultivating their solutions. The planner supports their fight without advocating in their name, connects different disadvantaged groups and prepares them to devise alternatives outside the existing system (Kinyashi, 2006).

The *Bargaining Model* describes the act of giving and taking between active participants (bargaining) as this model's most crucial decision-making aspect. This theory acknowledges the existence of disadvantaged and disenfranchised groups but accredits them the ability to influence decisions with at least the power to vote, demonstrate or provide information (Lane, 2005). Stakeholder involvement and bargaining are key elements and central dynamics in the decision-making process.

In *Communicative Planning*, stakeholders are brought together and involved in the decision-making process, and all their respective positions are recognised in the process. This planning theory aims for a consensus-driven outcome (Innes, 1992). This approach assumes that all knowledge is socially constructed and that people communicate and reason differently and are imprinted by their social context. The planner ensures communication between the stakeholders while assisting them to understand each other (Lane, 2005). The planner's role shifts from a neutral expert or logical analyser to an actor. Furthermore, the planners' own experiences and ways of communication and their position of power affect the planning process.

4.1.3 Key Principles in Spatial Planning

When it comes to spatial planning, one of the main issues is that competing interests regarding land use have to be mitigated and agreed upon. Therefore, the main aim is to find an acceptable compromise between the parties affected by the planning outcome to guarantee a sustainable use and protection of the resources while ensuring a smooth and efficient implementation of projects.

FAO (2015) describes the following key principles that help to define spatial planning and knowledge requirements that ought to be provided by the planning institutions as well as principles that should be comprised in the planning process (see Table 5).

Table 5. Key principles in spatial planning sorted by key principle groups

	Key Principle Groups	Principles
1	Stakeholder involvement	▪ Dialogue based ▪ Inclusive process ▪ Civic engagement
2	Locality	▪ Local conditions ▪ Local knowledge ▪ Local strategies
3	Laws and policies	▪ Subsidiarity ▪ Proportionality
4	Level	▪ Vertical level ▪ Horizontal level
5	Capacity and transparency	▪ Stakeholder improvement ▪ Transparency
6	Outlook	▪ Future ▪ Iterative process

Nowadays, stakeholder involvement is an indispensable part of the spatial planning process. Stakeholders should be included throughout the entire planning process and get a chance to express themselves in mutually respectful dialogue. The locality – including the local conditions and local knowledge as well as habitual problem-solving strategies – represent another key principle of the planning process. Stakeholder improvement does not stop at the inclusion and goes even one step further. It seeks to improve the stakeholder's capacity to plan and act and improve their conditions in general. Transparency about data and future intentions should be ensured at all times.

Furthermore, the level of planning is essential, and vertical and horizontal permeability should be assured. Vertically refers to different hierarchical levels of planning entities and stakeholders cooperating, communicating, and deciding together. Horizontally states the importance of working across different disciplines. It is essential to locate the spatial planning at its administrative level and, if possible, decentralise it (subsidiarity). Spatial planning strategies often entail restrictions on the use of land or natural resources. These restrictions should be proportionate and balance between restraints and citizens' responsibility.

The spatial planning extent should include the status quo and include future projections. The process must be oriented towards an iterative process where spatial planning is constantly updated and improved when new data and information is obtained.

4.2 Spatial Planning Practices

4.2.1 Spatial Planning Approaches for Protected Areas

When it comes to resource protection, the implementation of protected areas is a standard measure to avoid deterioration and ensure the future existence of outstanding natural formations. In 1864, the first formal protected area was introduced as the Yosemite Grant Act in the United States. In 1872, the Yellowstone National Park was developed as the first National Park (Watson et al., 2014). However, National Parks are just one step in the protected area movement. Nations started to develop and join international agreements and treaties, became members in environmental associations, passed bills, introduced their environmental protection laws, and established environmental ministries.

Since the beginning of the 20th century, there has been an incredible rise of efforts to protect the natural environment, and the number of NGOs, IGOs (intergovernmental organisations), national parks, ministries and environmental laws was growing exponentially during that time interval (Frank et al., 2000). However, protection efforts are driven by increasing economic affluence and environmental damage.

Today, 5.6% of the Earth's surface is designated as natural protected areas (Watson et al., 2014). Figure 7 illustrates the increasing number of protected areas and the increase in the absolute coverage of protected areas.

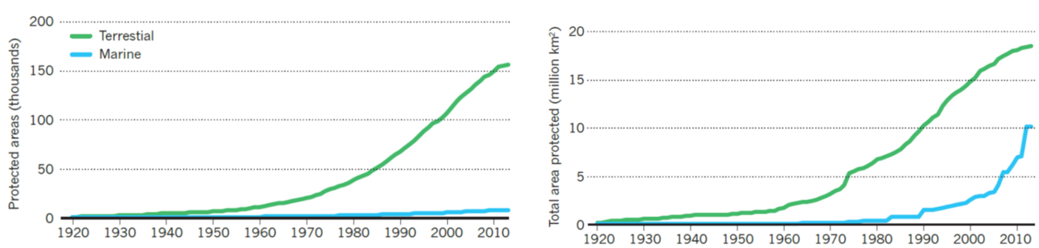


Figure 7. Advance of the protected areas worldwide in number of protected areas (left) and in protected spatial area coverage (right) (Watson et al., 2014)

The original aim of protected areas was the pure conservation of resources, landscapes, and biodiversity, but today there are increasing expectations to conserve even social and economic interests when converting an area into a protected area. A reason for that increasing diversification was the fast growth of protected areas that conflicted with the necessities of local communities. Today's objectives reach even further as they are attentive to the preservation of ecosystem services. The use of ecosystem services addresses the competing local interests and balances them.

Recently there has been an increasing focus on preserving the global ecosystem. The focus is shifting from protecting only local resources towards global preservation efforts (Frank et al., 2000). Expanding spatial boundaries when assessing local protection efforts and integrating other sustainable goals will be part of our future protection efforts.

4.2.2 The Spatial Planning System in Sweden

In order to understand the Swedish spatial planning system, it is essential to describe the country's administrative structure. Sweden is a constitutional monarchy with a strong federal system.

At the national level, the ministries have limited staff but are supported by topic-specific agencies. The leading responsible authority for spatial planning at the national level is the ministry of environment (Larsson, 2006) up until the end of 2022. The Ministry of Environment will be dissolved by December 2022 and its responsibilities will be overtaken by the Ministry of Enterprise and Innovation. At the time of this thesis, the takeover is in a transition period and the new responsibilities have not been clearly outlined yet. Table 6 lists responsible authorities within Sweden’s administrative structure for spatial planning and Figure 8 illustrates the Swedish planning system.

Table 6. 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.

	Responsible Authority	Responsibilities
National level	Ministry of Environment, Ministry of Finance, Ministry of Infrastructure (supported by Boverket[1], Naturvårdsverket[2], Trafikverket[3])	- Legal proposals - Define directions concerning planning
Regional level	State county administration and an elected county council	- Public health services - Promote county development - Recommend, instruct, and control municipalities
Local level	Municipal council	- Responsible for most spatial planning - Further responsibilities regarding infrastructure such as water and sewage work, sanitary, energy planning, parks etc.

[1]Boverket = National Board of Housing, Building and Planning, [2]Naturvårdsverket = Swedish Environmental Protection Agency, [3]Trafikverket = National Road Administration

The following administrative level is at the regional scale. The existing 21 counties in Sweden are individually governed by a county administration and a county council. The counties are highly independent of national administration to a point where the government cannot interfere with individual case decisions. Regarding spatial planning issues, a regional plan might be adopted if various municipalities necessitate coordinated action or describe the region's development direction. The regional plan is not legally binding for the municipalities but works as a decision-support tool.

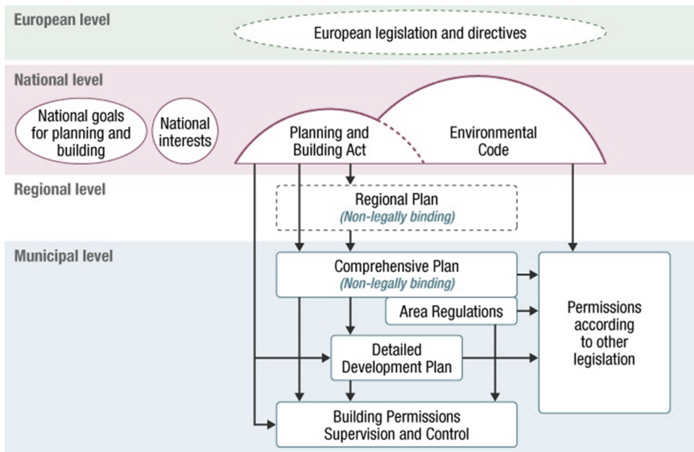


Figure 8. The Swedish Planning System (MLIT, 2014)

Sweden's lowest administrative level is built by 290 municipalities and run by an elected municipal council. The municipalities manage virtually all 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 regarding spatial planning in Sweden. Sweden has a strongly decentralised public administration, and the practice of municipality-led planning is often referred to as the "municipal planning monopoly". For each municipality, a comprehensive plan is developed and revised every five years to indicate how resources should be used and to ensure that national interests are respected at the municipal level. If necessary, a detailed plan might be developed for parts of the municipality where major expansions or changes require in-depth planning. Plans at each administrative level (national, regional or municipal) serve only as a decision support tool but do not comprise any legally binding character (Larsson, 2006). But once established, detailed plans are legally binding whereas general plans are not.

4.2.3 Spatial Planning for Protected Areas in Sweden

With increasing problems involving insufficient drinking water and wastewater treatment due to Sweden's industrialisation at the end of the 1800s, the *Health Protection Act* was enacted in 1874 (Naturvårdsverket, 2017). This new legislation included regulating natural resource extraction, protecting humans from the impacts of environmentally hazardous activities, and land use regulation for various purposes.

In 1909, Sweden was the first country in Europe to create nine national parks and enacted the Nature Protection Act (Naturvårdsverket, 2017). This was a groundbreaking piece of legislation since legislation was implemented for the first time to protect nature itself. The first legislation specifically directed towards natural water sources was implemented in 1918 with the Water Act. This act regulated the use of water resources but focused on providing possibilities for exploitation (mainly hydropower). Its revision in 1983 aimed at a higher level of environmental protection but did not change the focus away from exploitation.

Today, Sweden has a complex planning system regarding the implementation of water protection measures (see Figure 9). For water sources, the protection efforts are guided by the WFD, and the DWD from a European level. The WFD informs the legislation in the Swedish Environmental Code. In Sweden, drinking water is regulated as food and is therefore under the control of the National Food Agency (in Swedish: *Livsmedelverket*), which is informed by the DWD. The county boards and municipalities are the ultimate authorities in granting permits and overseeing water protection measures. They are informed by the water authorities and the Swedish Agency for Marine and Water Management (Swedish: *HaV*). Then there are several agencies that are responsible for protecting resources from contamination (i.e., Swedish Environmental Protection Agency) and developing maximum limit values for contaminants (Swedish Geological Survey, Swedish Chemicals Agency). These limit values are, in turn, guided by European Directives and the Swedish Environmental Objectives. Ultimately, the Land and Environmental Courts grant environmental permits for potential water-contaminating activities, and the criminal courts dispute criminal charges regarding the source waters.

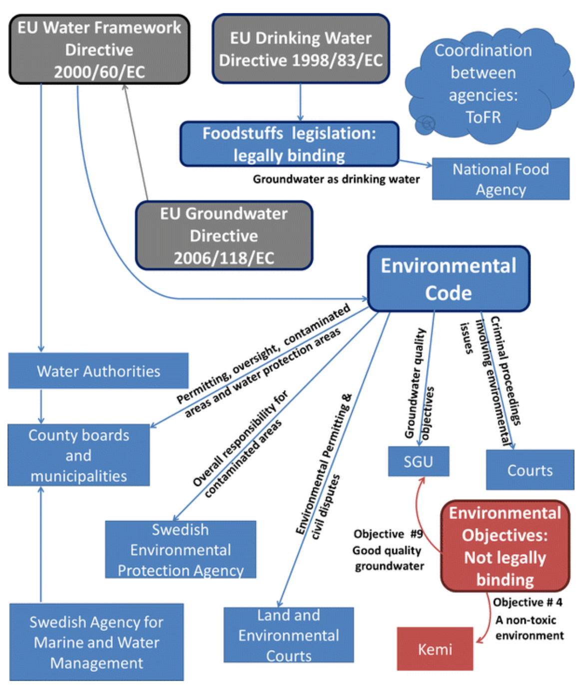


Figure 9. Swedish groundwater policy according to national law. Blue marked boxes indicate legally binding Swedish law, grey represent legally binding European law, and red is not legally binding. Note that the reference is from 2013 and is an example illustrating the complexity of the Swedish spatial planning system regarding water sources (from Lewis et al., 2013).

4.2.4 Indigenous Spatial Planning and Water Management Methods

In Western Societies, the main view on water is economical, whereas in indigenous societies, the dominant cultural perspective lies in spiritual attributes. Groenfeldt (2006) argues that the West has much to learn from the indigenous view of human's spiritual relationship with nature and that this ethical perspective in water management is missing in the Western toolkit. Following Groenfeldt's call to explore and learn from indigenous perspectives and insights on water, some interesting management techniques are presented from the island of Hawai'i, the Philippines, India, and South Africa.

Indigenous spatial planning and water management practices are often intertwined with a religious belief system. Water can be seen as a living being that provides life, is a relative, educates and is treated with affection or even a divine being, originating from the Gods and therefore being sacred (Iza, 2006; Norman, 2018). The protection methods are often identical to those Western societies implement in their water safety plans, but they rest on a different ideological foundation.

The water management of the people of Besao in the Philippines is directly related to the spirits of water that inhabit the water source. Under all circumstances, those spirits should be prevented from leaving said source (Bang-Oa, 2006). Actions that are seen to disrespect the spirits and make them leave include: transporting dead human and animal remains close to the water source (including butchering), grazing animals near or on top of the water source (manure and breath of cattle are seen as repulsive to the spirits), not receiving a sacrifice during the cleansing ceremony, and ploughing with animals on top of a water source. Sometimes the spirit does not leave the water source but is upset by the human's actions and therefore produces water to a lesser extent or triggers intestinal diseases. Furthermore, the Besao put a particular emphasis on the water sources' recharge area and on maintaining the forest cover sustainably. Trees in an allotment can only be cut down for personal use once in a generation and must be replanted. Since water is regarded as highly as land, it cannot be privatised and is a communal good (Bang-Oa, 2006).

For the Meitei people, an ethnic group in north-eastern India, water is one main component in the ancestral faith practice. Deities originate and return, communicate through and manifest themselves in the water and can even represent the embodiment of a God (Laifungbam and Pinto, 2006). Worship includes purification, the maintenance of water biodiversity and extensive natural groves through worshipping practices and rituals. Spatial planning practices are based on land zoning, partitioned for different uses: dry for habitation, flooding for rice cultivation, infiltration land used to infiltrate rainwater during the monsoon time and reservoirs for the dry season.

In the oasis village of Tagmachig in the Indian Himalayas, villagers attribute the existence of water as a response to people's behaviour towards nature. It is believed that people (mainly farmers) acquire water and can create it via their actions. Water deities will react destructive to pollution but gracious when attempted with purity. Rituals show the symbolic meaning of water and structure the agricultural responsibilities as villagers remind each other of the principles for water quality preservation, including the spring, the watercourses, and the remaining catchment area (Wacker, 2006).

Rules for water quality preservation are sometimes entangled with supernatural beliefs and punishments, and respect for water is transmitted via tales. For example, Khumbane (2006) outlines a legend about the elderly in rural South Africa. A man defecated next to the drinking water well and, as a result, grew a long tail and got nothing but scorn and derision from the village.

In Hawai'i, there is a trend towards reestablishing the traditional Ahupuaʻa land management concept, particularly with watershed planning. It is a decentralised environmental management model where activities are located within the management unit. The localisation is broadly based on respect for nature, water as a sacred means, access to resources and guarding ancestral places (Minerbi, 1999). Elders will express the correct management approach that matches tradition, but young people will decide if the decision concerns their future (Minerbi, 1999).

This view on indigenous water management describes autochthonous methods developed and used by indigenous populations. Usually, local communities hold the expertise in solving their problems and presenting solutions. Indigenous knowledge plays a vital role in environmental management. However, there is still a tendency by the scientific community to adjust local knowledge to our Western world views of environmental governance. Traditional knowledge is often only accepted if it fits our explanations and observations of established scientific principles (Ellis, 2004). The examples above present various indigenous communities' water protection and water management techniques. There is a growing visibility of local planning methods regarding spatial planning approaches and watershed planning.

However, another angle can be considered to assess indigenous spatial planning methods. This angle considers including indigenous people in the spatial planning process where governmental institutions manage the planning process. In contrast, indigenous people take, at best, the role of a knowledgeable and important stakeholder. Marshall et al. (2018) stress that indigenous involvement in source water protection programs is usually minimal, and their involvement is generally not described as significant. Jackson and Morrison (2007) describe indigenous representation in water planning.

Their traditional knowledge is accommodated in the planning process, but the beliefs and methods are not adopted (Ellis, 2004). Beltrán (2000) presents best practices and guidelines for enhancing synergies between indigenous stakeholders and planning institutions. A long list of publications stresses the importance of indigenous stakeholder involvement in environmental management techniques. This includes integrating aboriginal cultural values into water planning (Moggridge et al., 2019) and an indigenous cultural approach to collaborative water governance (Poelina et al., 2019).

4.3 The Practice of Water Protection lags behind the Theories of Spatial Planning

After the presentation of the different modern spatial planning theories, key principles and practices in spatial planning, I explore in this section the question of where the implementation of water protection measures can be located with reference to the theory and practice of spatial planning as presented earlier. Alternative practices for implementing water protection measures and corresponding theories of spatial planning are presented in Table 7.

Table 7. Water protection practices and their corresponding theories in spatial planning.

		Water Protection Practices	Corresponding Planning Theory	Problems
Comprehensive rational planning	1	Strict implementation of a calculated delineation area	Blueprint Planning	– Planners decide on the solution by themselves as a technical elite – The public does not participate in the process at all – Assumes one single unified public interest in the water source (to protect the water)
	2	Development of water protection measures with subsequent public approval	Synoptic Planning	– The public does not participate in the planning process – The public is only used to approve and legitimise the planning activities
	3	Development of water protection measures with comments from the public during the planning process	Mixed Scanning Model	– Top-down model

In the first practice, a planning entity establishes water protection measures based solely on technical knowledge and without modification. This planning practice corresponds to the theory of blueprint planning and involves various problems. Planners decide on the solution themselves and act as a technical elite. They additionally assume one unified public interest in the water source, which is protecting it. The public is excluded from the entire process. This first practice is seldomly implemented today and is not state of the art anymore. The second practice advances the first practice by subsequent public approval of the water protection measure. This practice corresponds to synoptic planning. The public is only used to approve and legitimise the planning activities but does not participate in the planning process. The third practice includes public comments during the planning process and corresponds to the mixed scanning model.

However, the practice of water protection measures is exclusively top-down planning methods and is based on comprehensive rational planning attitudes. In this ideal but impossible type of decision-making, the planner performs a comprehensive assessment where they review all choices and their effects and translate them into a decision.

Whereas these planning models are considered outdated in spatial planning, the practices are widely used to implement water protection measures today.

The practice of water protection measures did not yet advance into the sphere of theoretical pluralism and bottom-up decision-making. Stakeholder involvement is often solely pragmatic, due to personal relations and the information flow is unidirectional (Dawson et al., 2018). All modern spatial planning theories stress that the involvement of stakeholders is indispensable if long-term planning efforts are to succeed. Watershed-based communities should be involved in setting specific goals for groundwater use and should understand the fragility of the resource (Gleeson et al., 2010). We can learn a lot from recent spatial planning theories and be inspired by their principles to improve the implementation of water protection measures. Furthermore, indigenous spatial planning practices can inspire outside-the-box practices and guide future protection efforts.

5 Dealing with the Challenges of Water Protection Measures as a Spatial Planning Exercise

This chapter presents potential solutions to the challenges that the implementation of water protection measures poses.

5.1 Ecosystem Service Assessments

Drinking water sources are complex systems which provide a variety of benefits. It is often challenging to illustrate the full range of benefits consistently. Ecosystem service assessments can help to address this challenge and make the evaluation of WPM more comprehensive.

5.1.1 Ecosystem Services

Throughout history, people have always relied upon nature and well-functioning ecosystems. Ecosystem services (ES) can be defined as "the benefits people obtain from ecosystems" (Costanza et al., 1997). As early as the 1970s, Westman (1977) connected human welfare to functioning ecosystems and formalized this relation. Twenty years later, Daily (1997), Costanza et al. (1997), and the Millennium Ecosystem Assessment (MA, 2005) mainstreamed the concept of ecosystem services.

Since then, many classification systems of ecosystem services have been developed to assess ecosystem services thoroughly (e.g., 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)). CICES is a standardized classification scheme and is broadly accepted, recognized, and applied in ecosystem services research in Europe (Anzaldua et al., 2018; Kaval, 2019). This framework builds on earlier classification schemes such as TEEB and MA, and uses a cascade model as a conceptual framework (de Groot et al., 2010) in which a production chain links biophysical structures over various steps to the contribution to human well-being (see Figure 10).

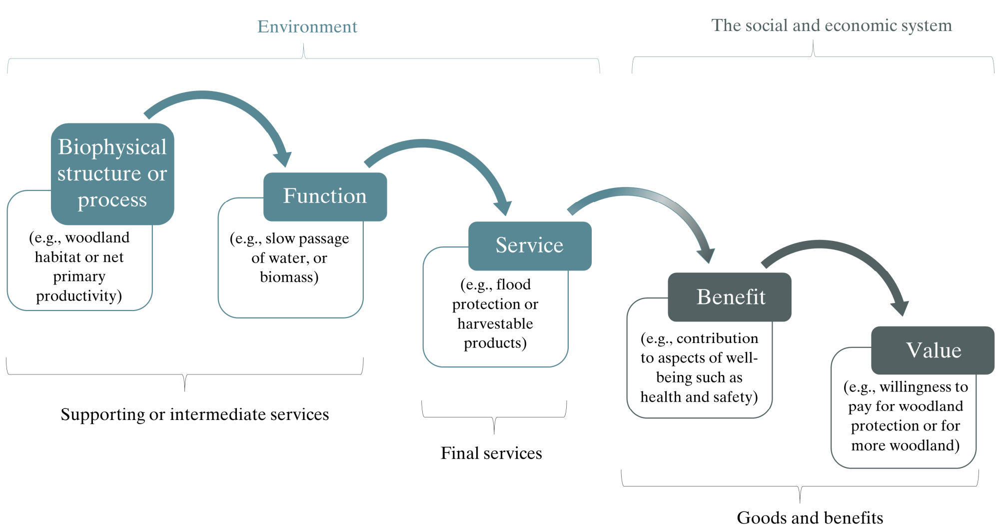


Figure 10. The CICES cascade model modified after (Haines-Young and Potschin, 2018a)

In the natural system, biophysical structures and processes provide ecosystem functions that generate ecosystem services. The actual use of a service in the social and economic system then provides humans with benefits that can be valued.

The hierarchical structure applied in CICES resembles a taxonomic approach used for categorizing organisms. Services are divided into sections (provisioning, regulating, and cultural services), then into divisions, groups, and classes, and finally, examples of services belonging to different classes are presented to provide further guidance.

5.1.2 Ecosystem Services in Spatial Planning

One of the limitations of spatial planning is that it is often unable to illustrate the advantages of landscape conservation and protection efforts (von Haaren et al., 2016). Whereas the trade-offs for restrictions and limitations are often clearly visible, the effects of prevented damages are less apparent. Avoided damages can be illustrated in spatial planning by ecosystem services, and the ecosystem service concept is rising in spatial planning (von Haaren et al., 2016). This concept has the potential to increase awareness about complex ecosystem interactions and offers a concept that unifies the values that people attribute to their landscapes (Fürst et al., 2014).

In modern spatial planning, the local community has an important role in the planning process and values are negotiated at the community level. Opdam (2016) argues that the valuation of ecosystem services is a social activity in contrast to an economic one. If stakeholders value a protection effort through a change in landscape, this change may be seen as profitable. Furthermore, spatial planning can be informed by creating inventories of ecosystem services that are used by different stakeholders and could create new allies between the different land users (von Haaren et al., 2016).

Ultimately, the integration of ecosystem services has the chance to advance environmental conservation and strengthen the communication of public goals (von Haaren et al., 2016).

5.2 Integration of Risk Assessments

In industrial nations, risk has become the most prominent organizing concept that drives environmental legislation (Jasanoff, 1999). However, when it comes to the protection of drinking water sources, it is impossible to abolish all risks towards the water source, and a certain amount of risk will always remain present. Therefore, risks must be assessed, managed, and mitigated efficiently.

The International Organization on Standardization (ISO) defines risk management as *coordinated activities to direct and control an organization with regard to risk* (ISO, 2018). ISO provides the gold standard on risk management (31000:2018) and establishes how risks should be managed effectively. Figure 11 illustrates the risk management process, which includes the risk assessment, subdivided into risk identification, risk analysis and risk evaluation.

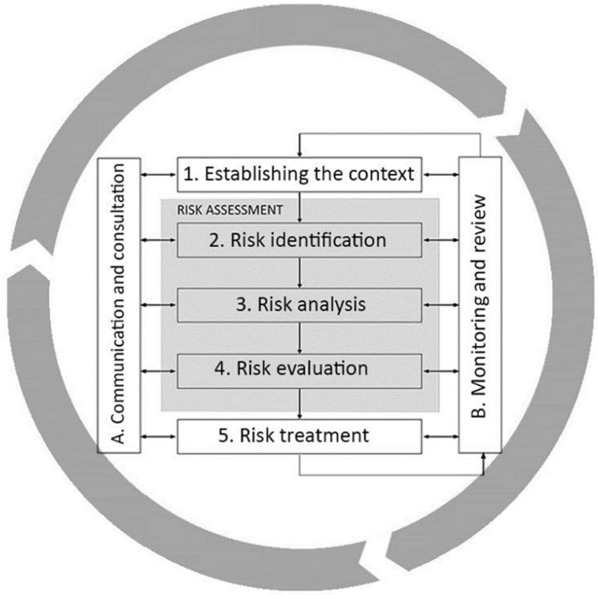


Figure 11. The risk management process based on ISO 31000:2018 (from (Laine et al., 2021))

Three types of risk assessment can be distinguished: qualitative, semi-quantitative, and quantitative risk assessments. Qualitative risk assessments express the risks in classifications or words (e.g., high/low risk, green-yellow-red labelling of risk categories). In contrast, quantitative risk assessments result in a risk description in numerical values. Semi-quantitative risk assessments form an intermediate category where the probabilities and consequences are described in qualitative terms but to allow calculations and facilitate comparisons, a number is assigned to each qualitative category. For example, the probability of an event to happen is described in words and a corresponding number (most unlikely = 1 to almost certain = 5). This allows its combination with a consequence described in words and numbers (e.g., no consequences = 0 to catastrophic consequences = 5). The result of semi-quantitative risk assessments is a scoring number for each risk that can be more easily ranked than pure qualitative results.

5.3 Environmental Justice

Since safe drinking water is a public health issue, health benefits should be equally distributed in a just society. Environmental justice research recognized that exposure to toxic wastes, landfills and other pollutants is systemic and increases social divides and inequalities between ethnic groups or socio-economic classes (Malin et al., 2019). Boone et al. (2009) refer to a just distribution as “an equal distribution of benefits and burdens among individuals or groups”.

The concept of environmental justice can therefore inform spatial planning for drinking water protection and is then able to identify and even out an unequal distribution of drinking water to different societal groups.

6 Papers

This chapter brings together the ideas identified in chapter 5 and applies them in the context of water protection measures. It provides a summary of the appended papers.

6.1 Paper 1: Combining Ecosystem Services with Risk Assessments for Drinking Water Protection

The overall aim of this study was to illustrate how the Ecosystem Service (ES) framework can be integrated into risk assessments for drinking water protection to ensure that the full range of services provided by the drinking water source is accounted for in decision-making.

We explain the process of modifying the ES framework to develop a region-specific list of services based on the classification of ES contained in *Common International Classification of Ecosystem Services* (CICES) (see Figure 12). We then present an adapted list of the CICES that allows a straightforward assessment of all biotic and abiotic services provided by a drinking water source, referred to as water system services. We illustrate a practical application of a Swedish case study by integrating ecosystem services into a risk assessment following WSP guidelines.

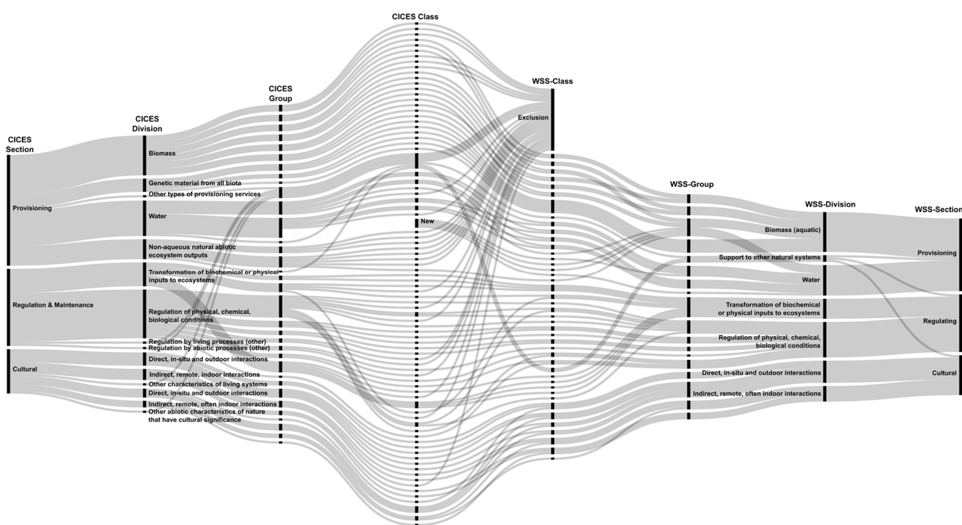
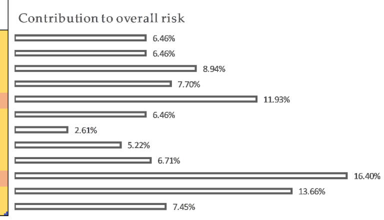


Figure 12. Transformation of the ecosystem service framework CICES v.5.1 into the water system services list (from Gärtner et al., 2022).

Based on this list, all services delivered by the aquifer at the case study site were identified via remote sensing and a site visit. As a next step, hazards towards the drinking water source were identified using the TECHNEAU database (Beuken et al., 2008). To illustrate the risk posed by each hazard as well as the overall risk the ecosystem services are exposed to, a risk priority number was calculated. We tested the feasibility of our approach on a case study site (Skallsjö aquifer) in Southwestern Sweden.

We found that the Skallsjö aquifer provides multiple services while simultaneously being pressured by twelve hazard sources. Our developed assessment matrix (see Figure 13) contrasts the hazard sources and their potential impact on each service. Based on the assessment matrix, we can identify the need for mitigation measures based on the hazard sources that are the most significant contributors to the overall risk or the sources that contribute the most to a service that is considered especially worth protecting. The services can be quantified to estimate the effect of measures to provide additional decision support.

	Provisional Services					Regulating Services			Cultural Services		
Hazards	Municipal DW supply	Household wells	Water for grazing horses	Irrigation of garden with well	Heat pumps	Prevention of subsidence	Quality control of freshwater	Springs regulating local temperature and humidity	Hiking in the green area around the spring	Looking at the springs	Option value
Tire and car company	32	32	32	32	0	0	16	0	16	16	32
Car service	32	32	32	32	0	0	16	0	16	16	32
Sewage network	48	48	48	48	0	0	16	0	32	32	16
Road E20	40	40	40	40	0	0	16	0	16	16	40
Heat pumps	48	48	48	48	36	0	24	36	24	24	48
Cultivated land	32	32	32	32	0	0	16	0	16	16	32
Football field	12	12	12	12	0	0	8	0	8	8	12
Motocross tracks	24	24	24	24	0	0	16	0	16	16	24
Forest activities	32	32	32	32	0	0	16	0	16	16	40
Impermeabilizations	48	48	48	48	48	48	12	60	60	60	48
Less precipitation	40	40	40	40	40	40	10	50	50	50	40
Overexploitation	24	24	24	24	24	32	8	24	24	24	8



No risk:	0	Low risk:	1 - 40	Medium to high risk:	41 - 100	Extremely high risk:	> 100

Figure 13. Assessment matrix contrasting hazard sources and their impact on water system services. Numbers from 0 (minimum risk score) to 125 (maximum risk score possible) in the matrix represent the calculated risk score for each hazard-service pair. The bar chart on the right indicates the contribution of each hazard source to the overall risk. (from Gärtner et al., 2022)

6.2 Paper 2: Including Environmental Justice in Drinking Water Protection

Many studies have found that minority and low-income populations are often supplied with a worse drinking water quality and are therefore exposed to higher risks for drinking water-related diseases and outbreaks (Bae and Lynch, 2022; Balazs et al., 2012, 2011; Delpla et al., 2015; Hales et al., 2003; Mueller and Gasteyer, 2021; Pace et al., 2022). However, these studies have mainly been conducted in the US, followed by Canada, South Africa, New Zealand and India, whereas no assessment has been done for Scandinavia. This study tests whether these disparities are also evident in Sweden. It focuses on drinking water sources in Gothenburg, Sweden, and includes different-sized municipal water utilities and private wells.

The overall aim of this paper was to analyse socio-economic disparities of drinking water consumption in Sweden using a case study region. To identify disparities, we assessed if environmental justice indicators (income, age, education, and place of birth) correlate with (a) the type of supply (private well or municipal drinking water supply), (b) unmonitored sources, (c) potential exposure to hazard sources, and (d) drinking water quality.

We perform a geospatial data analysis that enables the characterization of drinking water consumers and reveals information about the consumers' socio-economic status, their raw water source, the monitoring status, water quality, and the hazards the source water is exposed to. We intersect the geographic locations of the drinking water intakes and private wells with socio-economic datasets and conduct a correlation analysis, cross-sectional regression, and multivariate factor analysis.

We find that the consumption of untreated drinking water by private well owners is slightly more common for socio-economically advantaged communities. However, within the population of private well owners, consumers are equally exposed to risks independent of their socio-economic background.

Our approach can also be used as a decision tool for the prioritization of new area connections. The decision framework of planned connected areas incorporates various indicators such as financial aspects, age of the infrastructure, state of on-site sewer systems, and reported safe drinking water violations. However, decisions on new connections do not include environmental justice considerations (Schwetschenau et al., 2022). Adding the considerations of environmental justice adds to an equal society and provides a decision tool where planned connected areas can be determined by who is most likely to need them.

7 Discussion

7.1 Contributions of the Work

The performed studies contribute to the development of advancing the implementation of water protection measures in three ways.

The first contribution is the operationalization of ecosystem service (ES) assessments for assessing drinking water sources' contribution to human well-being. Due to its complexity, ES faced significant criticism for not being compatible with governance and management of water resources (Cook and Spray, 2012). The developed list of water system services provides an instrument to close this implementation gap.

The second contribution is the combination of risk assessments and ecosystem services. While an ecosystem service assessment for drinking water sources might not seem worth the effort, its combination with a risk assessment raises awareness of drinking water protection and supports the implementation of protective measures. The assessment adds to the WHO's approach by making it possible to motivate protective measures and comprehensively assess water sources more easily. Applying our approach to the Skallsjö aquifer demonstrates that integrating ecosystem services into a risk assessment is feasible. The approach provides valuable information for identifying and mitigating risks towards drinking water sources. The presented method is straightforward and does not require expert knowledge on ecosystem services.

The third contribution is the connection between environmental justice and the provision of drinking water which has not been done in Sweden before. The study does not only provide information on socio-economic disparities, but the developed method can be used to mitigate competing interests and reduce distributional injustices. Identifying consumer and provision patterns helps straighten potential inequalities in the provision of drinking water. Detailed knowledge about the consumers helps to identify stakeholders supplied by drinking water and facilitates outreach and stakeholder engagement. Furthermore, the results lay the foundation for developing more tailored risk assessment tools.

Additionally, this thesis illustrates the added value of cross-fertilization of different disciplines, especially with insights from the field of spatial planning, in implementing protection measures for drinking water sources.

7.2 Obstacles to the Practical Implementation of New Approaches

The performed studies and developed methods provide new approaches for implementing water protection measures. Nevertheless, there are some obstacles to the application of these new approaches and some cross-cutting issues that were identified during this licentiate.

7.2.1 The Spatial Planning System in Sweden

Some difficulties arise from the complexity of the Swedish planning system regarding the implementation of water protection measures. First, measures regarding water protection are ultimately decided by the 290 municipalities, but water bodies seldom follow municipal borders. No regional or national authority is specifically appointed to coordinate the implementation, leading to different extents of water protection approaches in each municipality. The result is a collection of scattered and sometimes incoherent protection efforts. Farmers, industries and other stakeholders facing restrictions in one municipality might feel unfairly limited if the restrictions in a neighbouring municipality differ for the same type of land use.

Second, municipalities have the legal competence to implement water protection measures but often lack the skills regarding water protection measures. Especially small municipalities often have limited resources and few employees in charge of all decisions regarding drinking water, wastewater, and waste management. As a result, assessments regarding water protection measures are often outsourced to consultancies which provide a report including the assessment and a proposed measure for the extent of the water protection. Due to the lack of technical competencies, municipalities cannot evaluate the consultancies' competencies and judge their methods. Therefore, municipalities often base their decisions on the consultants' recommendations.

7.2.2 Practitioner's Role

In Sweden, consultancies are often commissioned to analyse the need for protecting water sources and develop corresponding measures (Dawson et al., 2018). However, as profit-oriented businesses, consultancies compete on the market and, therefore, prioritise efficient production of results based on standardised and easily replicable methods. The definition of water protection measures that are more holistic and complex, and in line with the new Swedish guidelines on water protection areas (SwAM, 2021), will require consultancies to review their methods and approaches consequently. In consideration of always present budget constraints at the municipal level, new methods for developing water protection measures should be cost-efficient to enable widespread application and should provide additional and valuable results that motivate potentially higher costs for performing necessary assessments.

The new Swedish guidelines for protecting source water (SwAM, 2021) clearly demand using risk-based approaches over travel time criteria. However, practitioners often critique the lack of detailed instructions on how to assess a drinking water source based on risk. They lament the lack of new guidelines when simultaneously being discouraged from using established travel time criteria.

8 Where To From Here

This chapter outlines the most important steps in the upcoming work. It is guided by the challenges that have not yet been addressed (see 1.1) and the conclusions from the identified obstacles to the practical implementation of new approaches (see 7.2).

8.1 Integration of Uncertainties into Water Protection Measures

A key part of developing a water protection area is delineating and defining the contributing area. Especially for groundwater sources, which are inherently uncertain due to their (hydro)geological conditions, uncertainties should be integrated into the delineation process. Different analytical and numerical methods and software exist to delineate water protection areas for groundwater. However, basic calculations are regularly too simplistic, but numerical models are often too data intensive. Especially groundwater sources which are often small sources that suffer from data scarcity, cannot be sufficiently modelled with numerical models. The analytic element method (AEM) provides a potential intermediate solution.

The possibility of integrating parameter uncertainty (e.g., hydraulic conductivity, depths of the water-bearing layer, etc.) into an AEM-software should be explored to produce probabilistic protection zones. The used AEM-software is called TimML and is a program for modelling steady-state multi-layer flow with analytic elements. TimML is coded in Python and, therefore, open-source, allowing us to integrate additional settings. We aim to include the uncertainty in input parameters via probability density functions and ultimately run a Monte Carlo simulation. Additionally, conceptual model uncertainty regarding, e.g., geological boundaries may also be considered.

The development of such a tool addresses the demand for including uncertainties in delineating water protection areas. Furthermore, it provides practitioners with an easily applicable tool for the probabilistic delineation of groundwater catchment areas without compromising scientific accuracy.

8.2 Quantitative Risk Assessments

In Paper I, the risks towards the drinking water source were assessed semi-quantitatively. However, affected stakeholders often criticise the results of qualitative/semi-quantitative risk assessments and demand more accurate and reliable results. This justifies the need to perform quantitative risk assessments for hotly-debated water protection efforts. Furthermore, this PhD project is part of a research project (WaterPlan-project) that aims to provide results that facilitate cost-benefit analysis (CBA). A future study should aim at a method development which quantifies the risks towards a drinking water source. A detailed definition of consequences and the testing of appropriate tools for consequence severity will guide the quantification.

It becomes evident that by using a CBA, the assessment is limited to an anthropocentric, utilitarian, consequentialist, and high substitutability view on drinking water resources. There are multiple issues with a cost-benefit analysis, and there is a need to extend and adapt the general use of the CBA methodology. Wegner and Pascual (2011) propose a pluralist framework that accounts for various moral theories (consequential and deontological) and plural values (incommensurable and commensurable) towards nature. To include various theories and views, two methods seem appropriate. For one, multi-criteria assessment (MCA) methods can include multiple objectives and weigh and prioritize between them. This approach improves the utilitarian nature of CBAs by valuing incommensurable goods without assigning a monetary value to them but counting them towards the final evaluation. An MCA also gives room to deontological theories. Second, discursive interactions between scientists, decision-makers, and laypeople provide an opportunity to extend the anthropocentric view on our drinking water sources and include zoocentric, ecocentric, or biocentric views. These discursive approaches are deliberative methods and include consensus conferences, citizen juries, focus groups and deliberative polls.

In a future method development, which includes a quantitative risk assessment and a CBA, the shortcomings of the CBA method regarding natural resource management have to be considered.

8.3 Interregional Learning

Eighty-two per cent of all water-borne disease outbreaks in Sweden occurred in small supplies (Gunnarsdottir et al., 2017), making these systems especially vulnerable and in need of protection (Davison et al., 2005). However, small systems often lack the resources to do extended risk assessments and implement extensive protection measures.

Large drinking water systems are generally very complex. There are often situated close to urban centres, are under pressure from various hazard sources and comprise extensive treatment steps. These characteristics make every large system unique, and their risks are evaluated individually with extensive effort. Nevertheless, small systems are often similar to each other, and there is a possibility for generalisation and transfer of knowledge between different small drinking water supply (SDWS) from different regions. Furthermore, these characteristics of small systems make it possible to conduct a comparative study to extract interregional lessons.

The mere act of comparing national drinking water systems with other countries' systems has many benefits. For example, Japanese NGOs were more efficient in crisis response during the 2011 tsunami if they had previously worked and cooperated with poorer Asian nations such as India and Bangladesh than NGOs operating exclusively in Japan (Lewis, 2017). It can be argued that cooperation and interregional learning benefit the management of a drinking water facility. Ideally, we can identify and exchange procedures and approaches. However, the benefit of interregional studies is not only in the extraction and adoption of strategies. We do not necessarily have to copy management strategies from one place to another. The benefit of interregional learning reaches further, similar to learning a new language which improves the awareness and skills of the mother tongue. If we look with the eyes of another system into our drinking water management, try to characterise and identify our system, and then compare it to another system, this procedure in itself renders results that benefit the understanding of our system and will eventually improve our system.

A first preliminary assessment gives an overview of the main factors that represent SDWS in Sweden and Rwanda. Even though the countries have very different features regarding geography, climate, and per capita income, they nevertheless have very similar features regarding the management and structures of their small drinking water supplies. Both countries have a significant part of the population that lives in rural areas, and the population is often not connected to a municipal drinking water supply. As a result, private landowners or small communities manage their drinking water supply suffering from little technological knowledge, constrained resources, and little inspection. In addition, wells in Sweden and Rwanda can be located in shallow aquifers, making them especially vulnerable to microbial contamination from sewage and agriculture.

Interestingly, even with very different financial points of departure, small drinking water supplies in both countries seem to face similar challenges which relate more to the management than to the actual financial constraint. Therefore, the results of this preliminary assessment indicate suitable locations and characteristics for representative case-study locations.

In the upcoming work, we will interview stakeholders at small drinking water supply locations in Sweden and Rwanda. We want to learn more about their management techniques, the procedures (official and unofficial) in place and why and how people manage their water supplies when confronted with disruptions or contamination issues. We are currently working on a questionnaire to guide our semi-structured interviews in both locations.

9 Concluding Remarks

Humans have had to make decisions regarding water since the beginning of civilization. The decision, e.g., to drink from a nearby but unknown river or walk further to a familiar spring, look for wood and boil the water before its consumption or consume it right away, was always part of people's routine. However, the problems have changed since ancient times, and the way we perform our decision-making has drastically transformed from intuitive and experience-based decision-making to data-driven, computer-aided, cost-based decisions.

The mere act of taking a decision is simple. Taking a responsible robust decision providing the optimal consequences is not. Source water 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 and trade-offs analysed. Furthermore, the solutions sought after often have to be provided with relative urgency, making it challenging to generate and analyse alternatives prudently. Decision-makers frequently attempt to achieve multiple yet conflicting objectives. There is often not one optimal way to mitigate a problem in these complex systems. There is instead a set of possible options decision-makers can choose from. Integrating dissimilar data and information calls for transparent methods and systematic structures.

By now, this thesis has shown that the implementation of water protection measures could improve by engaging with more modern theories of spatial planning. It also provided a method to comprehensively and efficiently map the many benefits that drinking water sources provide to society through the adaptation of the Ecosystem Services framework. Furthermore, with the newly developed risk assessment method, a broader range of consequences towards water system services is accounted for in the evaluation of the risks improving the representativeness of the landscape complexity. Lastly, this work showed that knowledge of distributional justice can be used in the prioritization of implementing water protection measures.

Eventually, we have to make a decision regarding the protection of drinking water sources, even though we will never have complete information. Or to say it with a famous German quote: *"The necessity to decide reaches further than the possibility to understand."* [1]

[1] *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 (Merkel, 2004).

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