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Water Safety Plan and Risk Assessment for Norrvatten from Catchment Area to Raw Water Intake

Water safety plan och riskbedömning för Norrvatten från avrinningsområde till råvattenintag

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The work for this thesis was carried out in cooperation with Norrvatten.

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Abstract

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This thesis explores the implementation of Water Safety Plans (WSPs) and risk evaluation methodologies, with a specific focus on Norrvatten's water management practices in the Upplands-Bro municipality catchment area in Sweden. The study area is only partially covered by the existing water protection area boundary, yet it is crucial as the water flows into the Görväln drinking water treatment plant in Lake Mälaren, given that the catchment area for Lake Mälaren is extensive, with a smaller area covered by the current water protection area zone. The study combines a comprehensive review of World Health Organization (WHO) guidelines, an overview of global WSP examples, and a case study of the Upplands-Bro area to assess current practices and identify opportunities for improvement in water safety management.

While Norrvatten's practices align significantly with WHO guidelines, there is potential for enhancement, especially in formalising the WSP approach and refining risk assessment methodologies. This research explores the comparative effectiveness of WSPs, the EU Directive 2020/2184, Swedish legislation, and current Norrvatten practices highlighting the challenges such as the complexity of accurately identifying and quantifying the study area's microbiological and chemical risks and the difficulty of prioritising risks based on their impact to Norrvatten's raw water source. Key findings underline the necessity of continuous improvement in WSP implementation, improved data collection and analysis, and effective public communication in water safety management. The thesis concludes with recommendations for Norrvatten, offering suggestions for future research, such as developing advanced risk assessment tools using quantitative microbial risk assessment (QMRA) and implementing water safety plans and risk matrices for other catchment areas that are feeding Norrvatten's raw water.

Moreover, evaluating the long-term impacts of WSP implementation on water quality and public health outcomes using a proactive approach and handling future threats such as climate change, urbanisation and environmental changing conditions. Additionally, the current water protection area boundaries should be expanded to incorporate the study area catchment and to address the misalignment between the administrative boundaries and the hydrological realities. Finally, to strengthen collaboration with stakeholders, related authorities and consumers.

Keywords: Water Safety Plans (WSPs), Risk Assessment, Drinking Water Quality, Catchment Management, Norrvatten, Upplands-Bro, WHO Guidelines, Public Health, Water Resource Management

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Popular science summary

Water Safety Plan and Risk Assessment for Norrvatten from Catchment Area to Raw Water Intake

Rana Jabiribrahim

Safe drinking water is essential to public health, and Water Safety Plans (WSPs) are globally recognised frameworks for protecting it. This thesis focuses on how Norrvatten, a water provider in Stockholm, Sweden, applies WSPs to manage contamination risks in Lake Mälaren's catchment area. Lake Mälaren is a critical water source but faces threats from urban, agricultural, and industrial activities.

Norrvatten's practices align closely with WHO's guidelines, yet there are challenges. A major issue is that not all upstream areas feeding into Lake Mälaren are within protected zones, which limits control over pollution sources. This study uses a structured "risk matrix" to evaluate and prioritise contamination risks across specific sites, such as landfills and agricultural zones. Expanding the current water protection areas would improve safety by ensuring stricter monitoring.

International examples, like Australia's proactive approach after the Sydney water crisis and New Zealand's creation of an independent water safety authority, emphasise the need for continuous improvement. Techniques like Quantitative Microbial Risk Assessment (QMRA), used in the Netherlands, offer additional tools that Norrvatten could adapt to predict and manage contamination risks better.

In conclusion, strengthening Norrvatten's WSP approach through updated risk assessment, expanded protective zones, and enhanced collaboration with local stakeholders is essential. Proactive measures and adopting international best practices are key steps to ensure the safety and sustainability of Sweden's water resources.

Keywords: Water Safety Plans (WSPs), Risk Assessment, Drinking Water Quality, Catchment Management, Norrvatten, Upplands-Bro, WHO Guidelines, Public Health, Water Resource Management

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Abbreviation list

WSPs – Water Safety Plans

WHO – World Health Organization

DW – Drinking Water

HACCP– Hazard Analysis and Critical Control Points

WRM – Water Resource Management

Introduction

In the pursuit of global public health, the importance of ensuring access to safe and clean water has led the World Health Organization (WHO) to outline the Water Safety Plans (WSPs), serving as guiding frameworks for water management organisations (World Health Organization, 2022). WSPs, promoted by WHO since 2004, are increasingly recognised as the global standard for evaluating and managing public health risks associated with drinking water provisions (Ishii and Deere, 2014). This necessity corresponds with the broader international agenda outlined in Goal 6 of the Sustainable Development Goals (SDGs) 2015, spearheaded by the United Nations (WHO, 2015). The recognition of access to clean drinking water and sanitation as a fundamental human right was reaffirmed by the United Nations General Assembly on July 28, 2010, emphasising its pivotal role in enabling the realisation of all other human rights (WHO, 2022). Beyond fulfilling immediate needs, this acknowledgement underscores the imperative to address and mitigate health risks stemming from water contamination.

The SDG Target 6.1 introduces the concept of "safely managed drinking-water services," emphasising structured actions to prevent contamination throughout the water supply system. This represents a significant advancement from the Millennium Development Goals (MDGs) of 2000, reflecting a shift towards more comprehensive targets (United Nations, 2014). The new approach involves monitoring global water quality through direct measurements of faecal contamination and priority chemicals, encompassing approximately 150 high-priority parameters such as arsenic, chlorine, and fluoride, as well as microbial, accessibility, and radiological aspects (WHO, 2022). Despite progress made during the MDG era, challenges persist. According to the World Health Organization (2017), approximately 663 million people still do not have access to improved-quality drinking water, while at least 1.8 billion people rely on water sources that are contaminated with faecal matter. This gap necessitates increased attention to proactive water supply system management, making it crucial for policymakers and practitioners to embrace water safety planning more than ever (WHO, 2017).

For EU countries, the quality of drinking water has been regulated through the Drinking Water Directive 98/83/EC for the past two decades. This directive is currently under revision to meet more stringent standards, incorporating a risk-based approach formulated as Water Safety Plans (Gunnarsdottir et al., 2020). In Sweden, the management of drinking water is governed by the Swedish Public Water Services Act (SFS, 2006:412), which acts by the EU Directive and mandates an integrated approach to safeguard human health and the environment.

Furthermore, stands the Swedish water protection areas, which is defined by The Sea and Water Authority in Sweden as “a land or water area given by the county board or the municipality according to Ch. 7. Section 21 of the Environmental Code MB, which is declared as a water protection area to protect a groundwater or surface water supply that is used or can be assumed to be used as a water source”. The purpose of the water protection regulations is to manage identified microbiological and chemical risks to water resources or to prevent problems from arising. So, when establishing a water protection area, a risk assessment should be carried out, i.e. risks need to be identified, analysed and valued. These steps form the basis for the justification of the regulations for the area after protection areas are established to address an identified negative impact on raw water and limit ongoing activities or land use (The Sea and Water Authority, 2021).

Swedish water suppliers must adhere to the Swedish National Food Agency's (Livsmedelsverket) regulations, which include the application of HACCP (Hazard Analysis and Critical Control Points) principles, the HACCP principle is applied to drinking water safety as part of a broader risk-based approach to ensure water quality. This system was originally developed in the 1960s by a team from the U.S. company Pillsbury in collaboration with the National Aeronautics and Space Administration (NASA) and the U.S. Army Laboratories. It was created to ensure the safety of food for astronauts during space missions, where any contamination could be catastrophic. The goal was to design a system that prevented hazards rather than relying on final product testing (Bauman, 1990). In drinking water, HACCP is a preventive system that is part of a broader framework for water quality monitoring and safety, ensuring that potential hazards to public health are identified, controlled, and prevented at critical points in the water treatment and distribution process to prevent contamination and ensure the delivery of safe drinking water to the public. HACCP has key elements in drinking water, which are hazard identification, risk assessment and control points, preventive measures, monitoring, corrective actions, verification, documentation and record-keeping. Building on these principles of water safety, Norrvatten applies similar risk-based approaches to ensure that the drinking water supplied consistently meets the quality standards set by the Swedish Food Agency.

This study focuses on Norrvatten, a prominent water management organisation in the northern Greater Stockholm region, Sweden. Serving 14 member municipalities, Norrvatten is responsible for producing and distributing drinking water that meets the standards set by the Swedish Food Agency (LIVFS2022:12). Görvälnverket, which is governed by Norrvatten, is a major water treatment plant that was built in 1926 and is located in Järfälla, Stockholm with annual production of around 50 million cubic meters of drinking water; plays a critical role in the region's water supply system by treating and purifying raw water from Lake Mälaren to produce safe drinking water for over 700,000 residents across multiple municipalities including several major hospitals and Arlanda Airport. Norrvatten ensures the availability of safe drinking water, which is essential for the region's development and well-being, by safeguarding that the treated water meets stringent quality standards set by Swedish regulations.

The research specifically examines the Brobäcken, Prästtorpsbäcken, and Nygårdsbäcken catchments located in the Upplands-Bro municipal zone. Görvälnverket is located in the water protection area *Östra Mälarens vattenskyddsområde*, a water protection area which is set up by the Stockholm County administrative board and is used by both Norrvatten and Stockholm Vatten to protect and safeguard water.

A knowledge gap exists in understanding the impact of the misalignment between administrative boundaries and the natural hydrological realities of the catchments; this incomplete protection affects the overall effectiveness of water safety measures. In the case of the study area, the current water protection area does not fully cover this catchment, which contributes to raw water quality upstream of Norrvatten's operations at Görvälnverket. This incomplete coverage leads to reduced monitoring and control over these areas, potentially allowing pollutants to reach water treatment facilities undetected, reducing monitoring and control over this area. The research gap also exists in reviewing case studies from other countries. Learning lessons from international practices to safeguard water resources could provide insights for Norrvatten, helping to enhance its protection measures. Furthermore, evaluating how closely Norrvatten's current practices align with WHO guidelines will offer a clearer path for improvement.

Despite the global emphasis on water safety through frameworks like the WHO's WSPs and EU Drinking Water Directives, a critical knowledge gap exists in assessing how well these frameworks are applied in specific local contexts. Current literature focuses on the broad implementation of WSPs globally and across Europe but often lacks specific case studies that examine unique regional challenges, especially in areas where administrative boundaries and hydrological conditions are misaligned. This gap affects the water safety measures, as is seen in the study area's partial monitoring coverage in certain catchments. This study thus aims to bridge this gap by examining water safety practices in Norrvatten's Swedish context, aligning them with international best practices to highlight areas for improvement.

Aim and Objectives

This research aims to explore various aspects of Water Safety Plans (WSPs) and their implementation, with a specific focus on Norrvatten's water safety practices in the context of Swedish water management.

The objectives of this research are as follows:

1. To review WHO guidelines for drinking water quality and compare them with EU directives and Swedish legislation standards.
2. To compare and analyse different examples of WSPs implemented globally, assessing their effectiveness and identifying best practices and approaches that could apply to Norrvatten.
3. To implement risk evaluation through a risk matrix for the study area (Brobäcken, Prästtorpsbäcken and Nygårdsbäcken catchments) based on the findings and recommendations from the analysis and assessments conducted throughout this study.

Method

Regulation Review

The methodology employed in this study is a literature review outlined by the World Health Organization WHO for "Guidelines for Drinking Water Quality,2022". The WHO guidelines were read deeply to write a summary of it and to extract a checklist table for Norrvatten that can be used with any water supplier to check how far they comply with the WHO guidelines. The checklist focused on the chemical and microbiological contaminations to raw water and catchment contamination sources. A quick review was employed to the guidance on the establishment and management of water protection areas by the Swedish Sea and Water Authority and Norrvatten's approaches to understand the regulatory framework within which WSPs operate.

WSP Examples Analysis

A literature review was made for WSP general understanding using Uppsala University online library, Scopus and Google Scholar databases. For this purpose, some keywords were used. To identify different examples of WSPs globally, other keywords were used. These WSPs were analysed and compared to commonalities, best practices, and variations in implementation approaches presented in a summarised table. Additionally, the study will investigate how water producers choose to implement these regulations and the tools they employ in the process, such as modelling, risk analysis, spatial boundary delineation, and data utilisation. Some data presented by (Table 1) were achieved through official online websites.

Table 1. Keyword searches and online websites.

Key words search	**Number of search results**
Water Safety Plan	567
Water Safety Plan Examples	565
Water Safety plan AND Water Management	80
Water Safety Plan AND Europe	45
Water Safety Plan AND case study	71
Water Safety Plan AND global	78
Water Safety Plan AND Risk Assessment	215
Water Safety Plan AND Risk Matrix	14
Drinking Water AND World Health Organisation	397
Official Websites	**Link**
World Health Organization	https://www.who.int/
Swedish Agency for Marin and Water Management	https://www.havochvatten.se/en/start.html
Water Safety Plan Portal- IWA	https://wsportal.org/what-are-water-safety-plans/

The study includes a review of twelve WSPs from a broader range of countries to examine how different regions define and implement risk criteria within their water safety frameworks. These twelve WSPs were selected based on a literature review and represent a diverse sample of risk matrix scoring criteria and management approaches by comparing these criteria—such as risk rating definitions, likelihood and severity scales, and threshold levels for action. This review provides various methods used globally to assess and manage risks. The overview of these examples serves as a basis for developing a customised risk matrix for Norrvatten, helping in finding the best practices in water safety planning and adapting them to local conditions.

In addition to the risk matrices of twelve countries, the study includes case studies of five countries—Australia, the United Kingdom, New Zealand, the Netherlands, and Canada—which were selected as case studies to examine different applications of WSPs. These countries were chosen due to their status as developed nations with well-established water safety frameworks, making their practices and lessons especially relevant for Norrvatten. Each case presents learned lessons in managing water safety, from proactive risk management and regulatory integration to advanced risk assessment techniques and stakeholder engagement. Reviewing these examples can guide the development of a WSP for Norrvatten.

Risk Assessment Development and Risk Matrix

To implement a methodically, a WSP proceed through several key steps. Firstly, it systematically identifies potential hazards and evaluates how often they occur. Secondly, it translates these hazards into risks, assigning priority based on their severity. The plan then implements operational monitoring of barriers or control measures to effectively mitigate these risks. Additionally, WSPs focus on enhancing documentation practices to maintain comprehensive records of safety measures and responses. Key factors for a successful WSP implementation include ongoing risk reduction strategies, innovative technologies, and emphasising process improvements (Jayaratne et al., 2023). Continuous improvement necessitates regular risk reviews, especially after incidents, whether they are predictable, unplanned or emergency incidents as classified by the WHO guidelines, to address challenges and implement short--, medium--, and long-term improvements (WHO, 2022). Audits play a crucial role, encompassing system audits and field activities conducted by skilled utility compliance officers (WHO, 2022). The general steps that guided our review of Norrvatten's practices to implement WSPs are shown in the figure below (Figure 1).

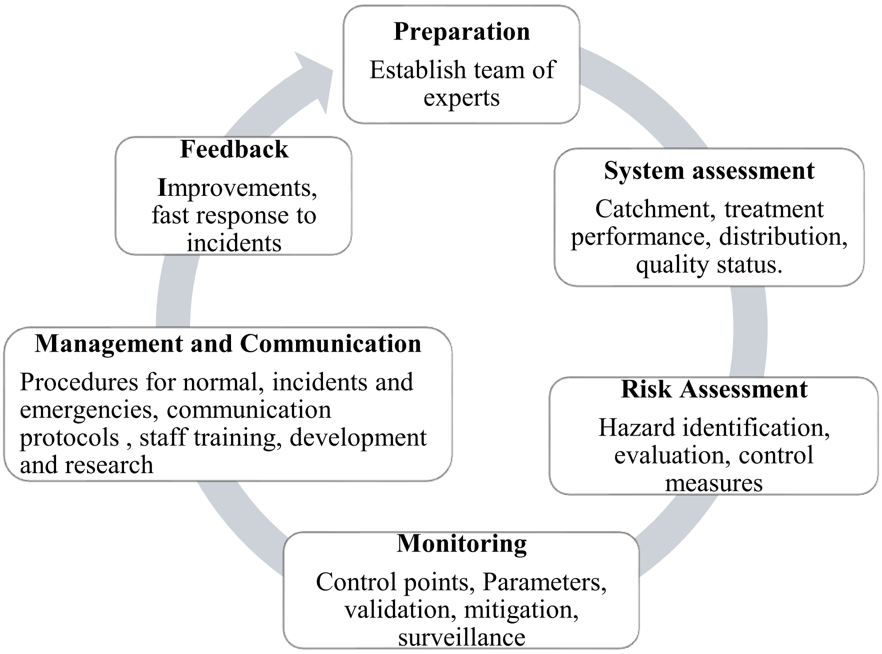

Figure 1. General processes for WSP.

This study focuses on implementing the risk assessment phase of developing a WSP for the catchment area up to the abstraction point, which served as a foundation for developing a risk matrix. Following WHO guidelines, potential hazards and hazardous events are identified, assessed and evaluated for the level of risk each poses to water quality. According to the WHO (2022), "a hazard is a biological, chemical, physical or radiological agent that has the potential to cause harm. A hazardous event is an incident or situation that can lead to the presence of a hazard (what can happen and how). Risk is the likelihood of identified hazards causing harm in exposed populations in a specified time frame, including the magnitude of that harm and/or the consequences".

Based on the literature review, a WSP approach is being implemented to closely collaborate with the study area. This includes developing a risk matrix by identifying risk sources in cooperation with Upplands-Bro Municipality and utilising the data provided by them. The data are provided as annual reports and GIS shapefiles in addition to open-source data. A risk evaluation is conducted to enhance the risk matrix. Finally, the risks are visualised and presented by creating a GIS map.

The data analysis process begins with forming a team of Norrvatten experts and Upplands-Bro Municipality staff, each bringing specialised knowledge to identify and assess risks to Norrvatten's raw water. The team was composed of the Process and Development Engineer with cooperation from the Upstream Manager, Head of Quality and Development, from Norrvatten and Environmental Inspectors, Industrial Inspectors, and additional key staff members from Upplands-Bro Municipality. The team conducted an area scan, identifying and categorising potential risk sources. Each identified risk is categorised into several types, including chemical, microbiological, agricultural pesticides, petroleum, and microplastics. Risk classification is based on its type and potential sources in the region, such as nearby agricultural areas, industrial sites, or urban runoff points. After categorising each risk, the team assessed it through an evaluation process.

For each identified risk, the team applied a likelihood and severity index. The likelihood was determined by analysing historical data on similar risks in the region and evaluating factors like known contaminant levels and activity frequency. Severity scores were assigned based on the potential impact of each risk type on water quality and public health, drawing on standards from the WHO, EU, and Swedish regulations.

To effectively manage water safety, the WHO recommends using a risk matrix to prioritise hazards and to evaluate the potential hazards for the Norrvatten water supply system, a risk matrix was developed by assessing both the likelihood of occurrence and the severity of consequences for each identified risk source. Each risk source was assigned probability and severity scores, with the final risk score calculated by multiplying these two values. This method allows for an overview of the risk landscape, enabling the prioritisation of mitigation efforts based on the calculated risk scores. The resulting matrix provides a visual representation of the relative risks associated with various potential contamination sources in the catchment area, aligning with WHO recommendations for structured risk assessment in water safety management.

A risk matrix is created with the selection of implementation criteria of the previous factors. The risks were plotted on the risk matrix, and each risk was assigned a score that translated to risk levels ranging from low to very high. This scoring system was adapted to meet specific criteria relevant to Norrvatten, such as the impact on water intake points and raw water supply continuity.

Finally, risk scores are calculated, rated from low to very high-risk levels, and visualised using a Geographic Information System (GIS) tool to create a risk map to illustrate the spatial distribution of evaluated risks and how risks would affect Norrvaten's raw water.

Each risk source was geolocated based on its coordinates, and the associated risk scores were layered onto the map to show the spatial distribution of potential threats. Assumptions made in this process included:

- Risk sources that were closer to water intake points had a proportionally higher likelihood score due to greater direct impact potential.
- Areas with multiple overlapping risk sources were treated as cumulative risk zones, with their scores adjusted to reflect heightened threat levels.
- Temporal data (e.g., seasonal pesticide usage) was considered to reflect periods of increased risk for specific contaminants.

Finally, the GIS mapping tool provided a layered visual of the risk levels, using colour codes to distinguish between different risk levels (e.g., green for low risk and red for very high risk). This visualisation allowed Norrvatten to prioritise areas requiring immediate mitigation actions and offered a clear depiction of how specific risks could impact raw water sources over time.

The risk matrix is a 5x5 grid, with the vertical axis representing severity (1-5, least to most severe) and the horizontal axis representing likelihood (1-5, least to most likely). The matrix cells were colour-coded to represent different risk levels: green for low risk, yellow for medium risk, orange for high risk, and red for extreme risk. The risk matrix shown in (Table 2) was built in the grid. The rating and definitions are presented by (Table 3) are used to evaluate each risk.

Table 2. Score matrix for ranking risks (WHO, 2022).

Severity of consequences	Rare	Unlikely	Moderately Likely	Likely	Almost certain
Catastrophic	**5**	**10**	**15**	**20**	**25**
Major	**4**	**8**	**12**	**16**	**20**
Moderate	**3**	**6**	**9**	**12**	**15**
Minor	**2**	**4**	**6**	**8**	**10**
Insignificant	**1**	**2**	**3**	**4**	**5**

Likelihood

Risk score	<6	6-9	10-15	>15
Risk rating	Low	Medium	High	Very high

Table 3. Definition of likelihood and severity categories to be used in risk scoring (WHO, 2022).

Item	Rating	Definition
Likelihood categories		
Almost certain	5	Once per day
Likely	4	Once per week
Moderately likely	3	Once per month
Unlikely	2	Once per year
Rare	1	Once every 5 years
Severity categories		
Catastrophic	5	Public health impact
Major	4	Regulatory impact
Moderate	3	Aesthetic impact
Minor	2	Compliance impact
Insignificant	1	No impact
vulnerability: Other experts, such as (Gärtner et al., 2022), recommend incorporating vulnerability into the risk scoring matrix to provide a more comprehensive assessment of risks. For this study, vulnerability is not considered		
Ability of water source to withstand the effects of hazardous events		
Extreme	5	Cannot withstand hazardous events
High	4	Little ability
Moderate	3	Good ability
Low	2	Very good ability
Insignificant	1	Barely vulnerable

The Bonn Charter strategy, presented by the International Water Association (IWA, 2004), further specifies the use of WSPs in drinking water management. The guidelines on WSPs offer general descriptions of hazard identification and a method for qualitative or semi-quantitative classification of risks, which provides a useful structure for risk assessment and facilitates the ranking of risks as a basis for prioritising safety measures (Rosen et al., 2010). Qualitative methods for risk ranking, commonly used in various disciplines such as engineering, environmental, and industrial management, rely on qualitative, often subjective, estimates of probabilities and consequences, typically presented using a risk matrix. This secures a safe drinking water supply by minimising contamination risks from the raw water source (Sea and Water Authority, 2021).

Sensitivity and Uncertainty Analysis in Risk Assessment

To account for uncertainties in our risk assessment, we conducted a sensitivity analysis by adjusting the likelihood and severity scores. We created three scenarios as follows:

1. Original Scenario: Using the initial likelihood and severity scores.

$$\text{Original Score} = \text{Original Likelihood} \times \text{Original Severity} \tag{1}$$

2. Increased Likelihood Scenario: Adding 1 to the likelihood score while keeping severity constant.

$$\text{Likelihood-Adjusted Score} = (\text{Original Likelihood} + 1) \times \text{Original Severity} \tag{2}$$

3. Increased Severity Scenario: Adding 1 to the severity score while keeping likelihood constant.

$$\text{Severity-Adjusted Score} = \text{Original Likelihood} \times (\text{Original Severity} + 1) \tag{3}$$

This approach allows us to observe how small changes in either likelihood or severity affect the overall risk score, providing insights into the robustness of our risk assessment. To analyse and differentiate between the final scoring results considering sensitivity measures, three different scores are calculated: original score, likelihood-adjusted score, and Severity-adjusted score. By comparing these scores, risk sources can be identified which are most sensitive to changes in likelihood or severity. Risk sources with large differences between their original and adjusted scores may require more careful monitoring or additional data collection to reduce uncertainty. Also, this helps in determining whether risk prioritisation is robust to small changes in evaluation estimates and highlights areas where more precise data collection could improve risk assessment.

Boundary Conditions

The Geographical Scope of this study concentrates specifically on the contamination of raw water from the catchment up to the abstraction point of Norrvatten with particular emphasis on the Brobäcken, Prästtorpsbäcken, and Nygårdsbäcken catchments in Upplands-Bro municipality. Consequently, this focus may limit the direct applicability of findings to other regions with different environmental characteristics and anthropogenic activities. At the same time, this provides insights into localised contamination issues. It primarily delves into microbiological and chemical contamination. Other forms of water pollution, such as physical contaminants, are not extensively explored. Therefore, the findings regarding these aspects may be limited.

The study's analysis is based on data collected within a specific time frame, and changes in environmental conditions or contamination levels over time may not be fully captured. These temporal constraints could affect the accuracy and applicability of the study's findings to future scenarios. There are various external factors, such as weather patterns, land use changes, or regulatory interventions, may influence water contamination levels in ways that are challenging to fully predict or control within the scope of this study. While efforts are made to account for these factors, their complex and dynamic nature could introduce uncertainties into the study's findings.

Also, partial inclusion in the water protection area of the study area may lead to reduced monitoring and control over certain parts of the catchment. This partial coverage could potentially impact the comprehensiveness of the data and subsequent analysis. Moreover, the lack of global examples for WSPs, especially in Europe, may limit the findings. The study's concentration on Norrvatten's practices and the local Swedish context may limit the broader applicability of some findings to water management organisations in significantly different regulatory or environmental settings.

Hence, this study is subject to several limitations that should be considered when interpreting its findings. These limitations should be considered when considering the generalizability and long-term applicability of the study's findings and recommendations.

Literature Study

Water Safety Standards and Legislation

The transition from the Millennium Development Goals MDGs of 2000 to the 2030 Agenda for Sustainable Development Goals SDGs marks an evolution in global water management strategies. Specifically, Goal 6 of the SDGs reflects a more ambitious commitment to ensuring universal access to safe drinking water (United Nations, 2014). This approach goes beyond the earlier MDG focus, which primarily aimed to increase water access for underserved populations, often without adequately addressing the quality of water for those already connected. The new framework emphasises not just access but the safety and sustainability of drinking water, aligning with the principles of Water Safety Plans WSPs to proactively protect public health.

The significance of access to safe drinking water stands across various levels, national, regional, and local impacting health and development outcomes. During the SDG period, policy and planning must respond to monitoring data revealing unsafe drinking water. Thus, policymakers and practitioners embrace the concept of water safety planning now more than ever (WHO, 2017). Investments in water supply and sanitation infrastructure have been shown to yield substantial economic benefits in certain contexts (WHO, 2022). Moreover, the reduction in health-related issues and associated costs often outweigh the expenses incurred in implementing involvement measures, ranging from large-scale infrastructure projects to household water treatment methods (WHO, 2022).

Swedish Legislation for Drinking Water (LIVFS 2022:12)

Swedish regulations, based on the EU directive and WHO principles, emphasise adaptations that reflect local needs. Comparing this national legislation with WHO guidelines and EU standards gives an overview of regulatory alignment and adaptation, assessing the application of international frameworks in Sweden. Swedish drinking water legislation (LIVFS 2022:12) is adapted from EU directives, adhering to both EU standards and local requirements. These regulations, enforced by the Swedish National Food Agency, delegate responsibility to municipalities, which play a critical role in ensuring drinking water safety.

Recent years have seen Swedish national authorities emphasising the significance of a risk-based approach and the use of risk assessments to guide the implementation of water protection measures (Gärtner et al., 2022). Sweden's 290 municipalities are part of the water management, with local autonomy in decision-making and service delivery. Municipalities are legally obligated to ensure the provision of drinking water and manage associated risks (Bendz and Boholm, 2020). Their active participation is vital in identifying hazardous risks and chemical pollutants from various sources, contributing to the development and implementation of effective water safety measures.

EU Drinking Water Directive

The EU Directive serves as the regulatory standard across European countries, promoting harmonisation in water safety practices. Understanding this directive's alignment with WHO guidelines is critical for analysing Norrvatten's compliance with regional regulations. The EU Drinking Water Directive (2020/2184) builds upon WHO guidelines, enforcing quality standards and introducing new parameters, such as PFAS and microplastics, to address emerging contaminants (European Commission, 2020).

For the last two decades, most European countries have regulated the quality of drinking water through the Drinking Water Directive 98/83/EC. The directive is a legislative measure that aims to ensure the quality of water intended for human consumption for all citizens across the EU, following its recognition as a human right by the United Nations (Gunnarsdottir et al., 2020), emphasising the importance of access to safe drinking water as a basic human right. Since 1998, the quality of drinking water in the EU and the European Economic Area EEA member states has been governed by the Council Directive (Directive, 1998). The Directive 2020/2184 of the European Parliament and The Council, dated 16 December 2020, updates the previous one and addresses various aspects related to the safety and quality of drinking water. Member states are required to implement the directive into their national law by January 12, 2023, ensuring compliance with the updated standards and practices by the Directive 2020/2184.

The key objectives of the directive are to improve water quality standards by establishing strict quality standards, ensuring it is safe and clean. Also, it introduces a risk-based approach to monitoring water quality by assessing the entire water supply chain from catchment areas to consumer taps to identify potential risks and ensure preventive measures are in place. Moreover, updates new contaminants and the list of parameters to be monitored, such as PFAS and microplastics. The directive seeks to harmonise water quality standards across the EU, ensuring that all member states adhere to the same high standards.

While the directive is a separate legislative document created by the EU, it aligns with the WHO guidelines. Furthermore, the EU directive recommends the adoption of WSPs according to WHO guidelines, which are a key component of WHO's approach to managing drinking water quality. It is also recommended to proceed with the WSP approach in the current drinking-water directive legislation (European Commission, 2007)

Municipalities emerge as crucial contributors in this collective effort, offering essential data on diverse sources of water pollution. Their active participation forms the basis of strategies crafted to guarantee the supply of high-quality water to communities (Garcia and Thomas, 2001). This collaborative process involves the identification of hazardous risks and chemical pollutants originating from various sources, such as industrial activities, vehicular accidents, shipping spillways, PFAS contamination, agricultural pesticides, and landfill leachate. The engagement of municipalities goes beyond data provision; it is a focal component in the development and implementation of effective water safety measures.

This study undertakes a review and comparative analysis of three key regulatory frameworks: the EU Drinking Water Directive (2020/2184), Swedish national legislation (LIVFS 2022:12), and the WHO Guidelines for Drinking Water Quality. Each framework contributes to ensuring safe drinking water through different approaches, but their alignment and effectiveness in practice remain a key area for exploration.

This study assesses how Norrvatten's practices align with WHO’s recommended WSP approach, as well as how effectively the EU and Swedish frameworks integrate these guidelines. The comparative analysis identifies areas where Norrvatten’s practices can be improved by learning from international standards and ensuring better alignment with WHO guidelines. This assessment provides the strengths and weaknesses of each framework, helping to inform future policy development and improve water safety measures in Sweden.

Existing studies on WSPs, such as those by Gunnarsdottir et al. (2020) and Ishii and Deere (2014), have underscored the value of risk-based frameworks for ensuring drinking water safety. There is limited exploration of water safety implementation where natural and administrative boundaries do not align, which can limit monitoring and lead to gaps in water quality protection. Furthermore, while countries like Sweden have developed national frameworks in response to EU directives, there is little research evaluating the local adaptation of WSPs to unique regional needs. Addressing these gaps can provide a more practical overview for local water management organisations, like Norrvatten, in developing responsive water safety strategies.

Water Safety Plans WSPs

This section provides an overview of standards for drinking water safety, focusing on WHO guidelines. The objective is to examine WSPs as a framework and to understand how WSPS addresses water safety. WHO’s global guidelines establish the foundation for water safety practices worldwide and emphasise the adoption of WSPs for safe drinking water, according to the WHO Guidelines should pose no significant health risk throughout one's life (WHO, 2022). Infants, young children, the elderly, and those with weakened health are most vulnerable to waterborne diseases, especially in unsanitary environments. Individuals prone to waterborne illnesses may need extra precautions like boiling water. Safe drinking water is necessary for all regular household uses, including drinking, cooking, and personal hygiene.

Ensuring the safety of drinking water relies on implementing a "framework for safe drinking water" based on guidelines. This supports a preventive management framework with a risk-based approach, starting from the water source to consumption, and considering prioritising resources and focusing on substances posing significant health risks while developing framework standards. Drinking water standards vary across countries and regions, and there is no one specific approach. It is important to consider existing legislation on water, health and local governance. Typically, this framework is integrated into national standards, regulations, or guidelines alongside relevant policies and programs and stems from a framework known as the “Stockholm Framework”. In 1999, the Stockholm framework established that guidelines for drinking water, wastewater, and recreational water should integrate risk assessment, management options, and exposure control within a unified framework with quality targets. This approach uses risk assessment as a foundation for decision-making and includes three elements as follows:

1. Framework for safe drinking water: This includes health-based targets set by health authorities, including infrastructure, monitoring, planning, management and independent surveillance based on an evaluation of health risks.
2. Water safety plans, WSPs, are a preventive strategy for safeguarding drinking water, utilising a comprehensive risk assessment and risk management approach designed to navigate the complex landscape of potential risks associated with water sources from catchment to

consumer. This highlights the need to ensure the consistent delivery of safe and clean drinking water (WSP Portal IWA, 2024). WSPs involve:

- Risk assessment: to manage risks and system assessment to ensure the entire drinking-water supply can meet health-based targets, water quality targets, performance targets and specified technology targets by identifying risks from the water source to the consumer and managing these risks effectively. Including addressing challenges like climate change (e.g. intense rainfall leading to flooding) and demographic changes like urbanisation, which can affect both the quality and quantity of water.
- Operational monitoring of critical control measures to ensure that the water facility is working properly during processes for the drinking water supply.
- Management plans and strategies outlining assessment and monitoring procedures, actions during normal and incident conditions, communication protocols and documentation.

3. An independent surveillance system ensures the proper operation of the above-mentioned components. Complying with verification if the WSP is effective. This assessment can be carried out by the supplier, surveillance agencies, or a combination of both. Surveillance and quality control are best performed by separate, independent entities to avoid conflicts of interest.

Water Resource Management WRM is an integral aspect of the preventive management of drinking water quality. Prevention of microbial and chemical contamination of source water is the first barrier against drinking water contamination of public health concern. WRM and polluting human activities in the catchment influence water quality downstream and in aquifers. This has an impact on the treatment steps required to ensure safe water and preventive action may be preferable to upgrading treatment. The influence of land use on water quality should be assessed as part of WRM. This assessment should take into consideration:

- Extraction activities
- Land cover modification.
- Construction/modification of waterways.
- Livestock density and application of manure.
- Various forms of recreation.
- Road construction, maintenance, and use.
- Application of fertilisers, herbicides, pesticides, and other chemicals
- Urban or rural residential development, with particular attention to excreta disposal, sanitation, landfill, and waste disposal.
- Other potentially polluting human activities, such as industry, mining, and military sites.

WSPs are built upon principles like the multiple-barrier approach and hazard analysis. Implementing a WSP offers several benefits, including hazard assessment, improved monitoring, and better documentation. On the other hand, WSPs provide structured systems to prevent failures and include plans for emergencies like droughts or floods. WSP should undergo review and approval by the relevant public health authority to ensure it aligns with defined health and quality targets. Generally, WSP is achieved through several steps, including:

- Understanding the specific system and its capability to meet water quality targets.
- Identifying potential sources of contamination and methods for control.
- Validating control measures to manage hazards.
- Implementing a system for operational monitoring of control measures within the water system.
- Taking timely corrective actions to ensure a consistent supply of safe water.
- Undertaking verification of drinking water quality to ensure WSP implementation aligns with relevant national, regional, and local water quality standards or objectives.

Each step in implementing a WSP process affects the outcome by influencing how risks are identified and managed. Assembling a skilled team ensures diverse expertise guides decision-making. Documenting the system provides a clear understanding of the water supply, which is crucial for identifying hazards and assessing risks. Accurately mapping the system helps the team pinpoint critical control points. Decisions made in identifying and prioritising risks influence which control measures are implemented. Monitoring and verifying these controls ensure they work effectively, while well-developed management procedures ensure quick corrective actions during issues. Poor decisions at any stage can weaken the effectiveness of the WSP, leading to potential gaps in water safety. The steps of achieving a WSP according to WHO guidelines are shown in the figure below (Figure 2).

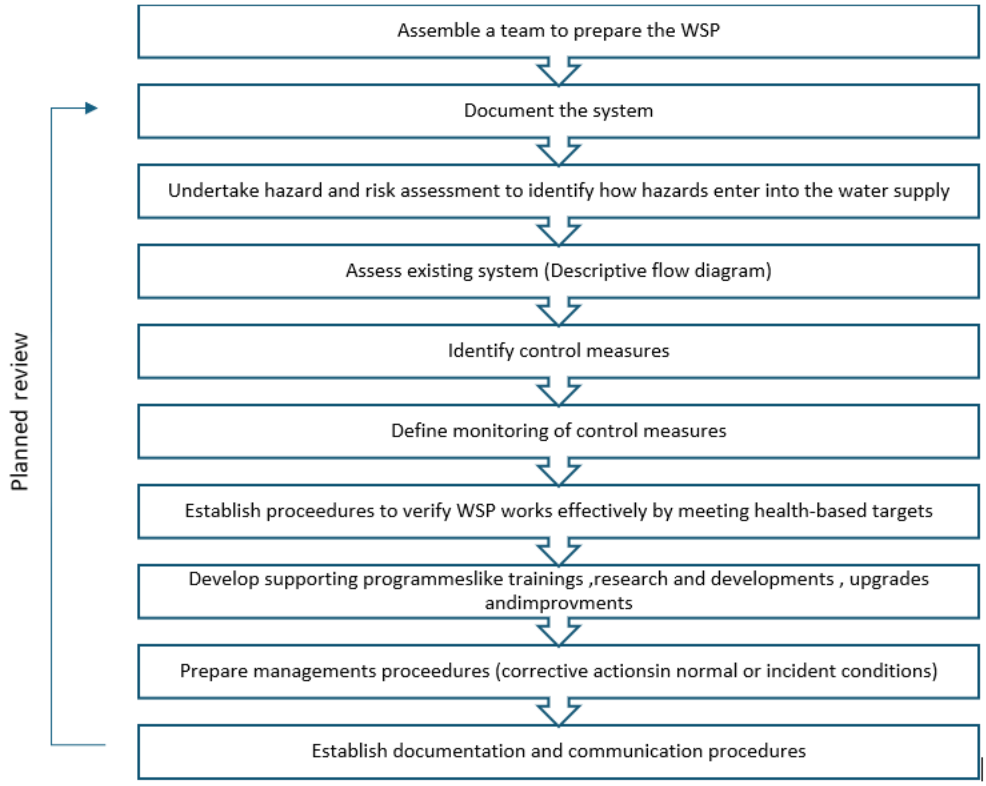

Figure 2. Steps of WSPs according to WHO guidelines (WHO, 2022).

WSPs comprise three main components: system assessment and design, operational monitoring and management plans, documentation, and communication. Each component addresses specific aspects of water safety, from identifying hazards and establishing control measures to ensuring effective management and communication of water quality information. The three components are as follows:

1. System assessment and design

   The assessment considers how certain constituents affect water quality, and hazards are identified and ranked based on their likelihood and severity. The WSP helps identify shortages and prioritise improvements. In cases of significant health risks, additional measures like notification, availability of alternative and emergency supplies, and spread of information are necessary.

2. Operational monitoring

   Operational monitoring ensures control measures in a drinking water system are functioning correctly. Limits for these measures can be set monitored, and corrective action taken if deviations are detected to prevent water from becoming unsafe. It typically involves simple tests to quickly confirm that control measures are effective in maintaining water safety. The monitoring plan includes the following:

   - Monitoring variable parameters.
   - Determination of water sampling locations and frequencies.
   - Sampling methods and necessary equipment.
   - Establishment of sampling schedules.
   - Inclusion of corrective action procedures with assigned responsibilities.
   - Qualifications and certifications required for testing laboratories.
   - Methods for ensuring quality assurance and validation of sampling results.
   - Procedures for checking and interpreting results.
   - Staff responsibilities and required qualifications.
   - Guidelines for documenting and managing records, including recording and storage of monitoring results.
   - Requirements for reporting and communicating results.

The goal is to monitor control measures promptly with a logical sampling plan. Parameters like turbidity, chlorine residual, or structural integrity are commonly tested. More complex tests are usually reserved for validation and verification rather than operational monitoring. Control measures should be proportional to the risk ranking of hazards. This involves identifying existing control measures, evaluating their effectiveness, and considering alternative measures if improvement is needed. Control measures should adhere to the multiple-barrier principle, where the failure of one barrier can be compensated by others, reducing the likelihood of contaminants reaching consumers.

3. Management plans, documentation and communication

A management plan outlines system assessment, operational monitoring, and verification procedures, including actions during regular operations or incident scenarios. It defines roles and responsibilities between agencies for effective coordination. For example, establishing mechanisms for stakeholder involvement as groups or partnership agreements. Especially when catchment management falls outside the responsibility of the water supplier, the level of detail should ensure operational control supported by competent operators. Regular review and updating of documents are essential to reflect changing circumstances facilitated by a document control system. Establishing incident reporting mechanisms and learning from incidents improves preparedness and planning. The documentation and communication should cover the following:

- Description and assessment of the drinking water system, including plans for upgrades and improvements.
- Operational monitoring and verification plan for the drinking water system.
- Water safety management procedures for normal operations, incidents, and emergencies, including communication plans.
- Description of supporting programs.
- Prompt notification procedures for significant incidents in the drinking water supply, including informing the public health authority.
- Providing summary information to consumers, such as through annual reports and online platforms.

Establishing mechanisms to receive and promptly address community complaints. In the end, The comparison between WSPs, EU directives, and Swedish legislation addresses the first research's objective and helps identify specific strengths and areas for improvement for Norrvatten's practices.

WSPs Status

Since 2004, WSPs have been promoted by WHO and are increasingly recognised as the global standard for evaluating and overseeing public health risks related to drinking water provisions (Ishii and Deere, 2014). WSPs gained global recognition as a modern strategy for mitigating health risks associated with drinking water. A survey conducted in 2013, which evaluates the implementation of WSPs specifically and also considers equivalent risk assessment and risk management approaches that may be utilised, shows that WSPs are presently implemented by at least 93 countries worldwide (WSP Portal IWA, 2024) and is adopted as either policy, or as a regulatory mandate, or is in the process of development (WHO, 2017).

In Europe, 41 countries out of 50 consider WSPs, nine countries have implemented WSPs, 13 are in the phase of implementing WSPs, and 19 are in the process of implementing a WSP by adopting and reflecting a commitment to proactive risk assessment and management practices (WSP Portal IWA, 2024). Examples of countries that have implemented WSPs are Norway, Switzerland, France, Iceland, and Slovenia (Gunnarsdottir et al., 2020). A list of countries' considerations for WSP practices according to (WSP Portal IWA, 2024) with different WSP statuses is presented by (Table 4). WSP statutes are presented by “implementind “ for countries that have fully implemented WSPs, “is implementing “for countries with partial or ongoing WSP implementation and “in progress to implement” for countries with limited or emerging WSP implementation.

Table 4. Countries in Europe and WSPs implementation status according to the International Water Association IWA (WSP Portal, 2024).

Number	Country	WSP Status
1	Albania	In progress to implement
2	Armenia	In progress to implement
3	Austria	Implementing
4	Azerbaijan	In progress to implement
5	Belarus	In progress to implement
6	Belgium	Implementing
7	Bosnia and Herzegovina	In progress to implement
8	Bulgaria	In progress to implement
9	Croatia	Implementing
10	Czech Republic	Implementing
11	Denmark	Implemented - Mandatory
12	Estonia	In progress to implement
13	Finland	Implementing
14	France	Implemented
15	Georgia	In progress to implement
16	Germany	Implemented
17	Greece	In progress to implement
18	Hungary	Implementing
19	Iceland	Implemented
20	Ireland	Implementing
21	Italy	Implementing
22	Kosovo	In progress to implement
23	Latvia	In progress to implement
24	Lithuania	Implementing
25	Moldova	In progress to implement
26	Montenegro	In progress to implement
27	Netherlands	Implementing
28	North Macedonia	In progress to implement
29	Norway	Implemented
30	Poland	In progress to implement
31	Portugal	Implementing
32	Romania	In progress to implement
33	Serbia	In progress to implement
34	Slovakia	Implementing
35	Slovenia	Implemented
36	Spain	Implemented
37	Sweden	Implementing
38	Switzerland	Implemented
39	Turkey	In progress to implement
40	Ukraine	In progress to implement
41	United Kingdom	Implemented- Mandatory

In Sweden, there are over 2000 water treatment plants, and according to the global status report on the water safety plan that was published in 2017, more than ten water supply facilities have implemented WSPs in the pilot phase. The WSP is formally approved as a policy or regulatory instrument for both rural and urban areas, with the need for an external evaluation.

While water is a crucial resource, it faces various threats like challenges in the provision of drinking water emerge due to social development and climate change. The future holds more frequent occurrences of climate change effects such as rising sea levels, heavy rainfall leading to floods, and increasing temperatures (Wheeler and Braun, 2013). According to the Swedish Public Water Services Act (SOU2021:81), the management of drinking water and wastewater must be approached to safeguard both human health and the environment, coordinating efforts to ensure safe drinking water while also effectively treating water to prevent pollution and environmental harm. Water protection regulations serve the purpose of managing identified risks to water resources and preventing potential issues from arising. WSP also accounts for long-term risks, such as climate change, which can impact water availability, quality, and infrastructure. By including risks from rising temperatures, changing rainfall patterns, and extreme weather events, WSPs ensure that water systems are resilient and adaptive to future climate challenges. Simultaneously, access to uncontaminated water is essential for the proper functioning of societies, human well-being, and the preservation of the natural environment (Sea and Water Authority, 2021). Meanwhile, according to the Drinking Water Committee report presented to the Swedish government in 2016 (SOU 2016:32), it is affirmed that "drinking water stands as the foremost critical support system in the country, serving as a fundamental necessity for the operation of society, businesses, and various activities." (Bendz and Boholm, 2020).

WSPs Benefits

WSPs change the way of management of water supply systems by representing a paradigm shift in water supply system management, moving from reactive measures to a proactive stance with continuous process chain monitoring. This approach allows for early detection of failures and prompt execution of corrective actions, safeguarding consumers from potential contamination before exposure occurs (Ishii and Deere, 2014). Moreover, they empower water service operators to evaluate the effectiveness of their entire water supply system, thus enhancing the management practices for both conservation efforts and quality enhancement. Preventive measures offer a proactive approach, for example, to averting waterborne disease outbreaks by fundamentally transforming water safety management. WSPs primarily focus on ensuring water safety and quality while also addressing quantity and security concerns, including strategies for minimising system losses through effective water resource management. (Ishii and Deere, 2014).

Contamination sources vary from pathogens, which are investigated only if an outbreak is suspected. E. coli and Enterococci are the main regulatory indicators for pathogens, signalling faecal contamination but not necessarily indicating a threat to human health. However, viruses and parasites may be present without these indicators, posing significant health risks due to their diverse survival strategies influenced by factors like temperature and strata composition. Parasites survive longer in water, while viruses can travel farther due to their smaller size (Figueras and Borrego, 2010). For example, a norovirus outbreak occurred in 2004 at a hotel in Northern Iceland, where 100 individuals were infected. Surprisingly, no indicator bacteria were detected, but water samples tested markedly positive for Norovirus (NoV) GII. Investigation revealed that the outbreak stemmed from a septic tank located 80 meters from the water well, upstream of the groundwater flow to the well (Gunnarsdottir et al., 2020). This addresses the importance of understanding groundwater flow dynamics for effective management before construction. This is why it is crucial to mitigate and develop technologies to measure pathogens, chemicals and other contamination indicators.

Moreover, the WSP approach is both financially and technically viable, as it has been shown to effectively reduce risks to water quality. By implementing WSPs, water suppliers can prioritise resources and focus on preventive measures, ultimately leading to safer drinking water and lower costs associated with contamination and treatment. However, this approach is not always reliable for monitoring all contaminants, and affordable water testing methods often struggle to detect most chemical and microbial contaminants (Ishii and Deere, 2014). Laboratories typically have limited capacity to test for pathogens. The WSPs redirect the attention of drinking water providers from a narrow focus on complying with numerical guideline values through endpoint testing (Gunnarsdottir et al., 2012). WSPs are powerful in systemically managing and assessing water safety risks as part of construction, operation, and infrastructure (Ishii and Deere, 2014).

The European Commission awarded a grant agreement to AQUAVALENS, which is a European Union-funded research project aimed at improving water safety by developing advanced technologies to detect waterborne pathogens and microbial contaminants in drinking water and other water systems. The project, which ran from 2013 to 2018, involved a consortium of 39 partners from various sectors, including universities, research institutes, public health organisations, water companies, and small and medium-sized enterprises. AQUAVALENS supports protecting the health of Europeans by improving methods for the detection of pathogens in drinking water and water used in food preparation. Five major water suppliers across Denmark, Germany, Spain, and the UK participated in AQUAVALENS. All had implemented a WSP, with WSPs being mandatory in Denmark and the UK. Two sites had WSPs certified as ISO 22000, and three followed WHO guidance (Gunnarsdottir et al., 2020). The benefits cited included infrastructure improvement, hazard identification, enhanced control processes, and increased user confidence. At the same time, drawbacks included cost, time consumption, and paperwork, although two suppliers saw no drawbacks. Overall, all five suppliers found WSPs beneficial, particularly in improving water safety and management (Gunnarsdottir et al., 2020).

In recent years, national authorities in Sweden have emphasised the significance of a risk-based approach and the use of risk assessments to guide the implementation of water protection measures (Gärtner et al., 2022). However, traditional risk assessment methods for safeguarding drinking water resources encounter various challenges although they use a risk-based approach similar to WSP, they rely more on reactive measures and typically focus on specific points in the water supply chain. For example, they might assess the risk of contamination at a particular source or within a specific treatment process. Meanwhile, WSPs rely on proactive measures covering the entire water supply system. This limitation may lead to suboptimal prioritisation of risk-reduction measures and an inefficient use of available resources (Rosen et al., 2010).

WSPs Challenges

Establishing a WSP and defining target water quality objectives are critical tasks. Challenges that may arise encompass discrepancies between WSP and water supply facility scopes, complex economic and financial assessments regarding mitigating public health risks and ensuring the enduring sustainability of WSP implementation (Ishii and Deere, 2014). It is fundamental to refer to the WHO guidelines when analysing risks. WHO defines risks as "the likelihood of identified hazards causing harm in exposed populations in a specified time frame, including the magnitude of that harm and/or the consequences" (WHO, 2022). The complexity and multi-faceted nature of risks such as microbial contamination, chemical pollutants, operational failures, and environmental changes underscore the difficulties encountered in offering WSPs a pragmatic and feasible method for risk assessment (Lane and Hrudey, 2023).

Additionally, risk ranking methods assume a discrete nature of hazards, cannot provide quantitative estimates directly comparable to performance targets, and typically do not include procedures for sensitivity and uncertainty analysis (Burgman, 2005). Include the added expenses associated with conducting risk assessments and a narrow focus limited to drinking water service alone. This limited perspective may overlook other vital services provided by water sources, such as expanding a water protection area, not only enhancing drinking water provision but also supporting additional services like recreational activities such as swimming, scenic tourism, livestock watering, or renewable energy initiatives like ground source heat pumps (Gärtner et al., 2022). Decisions solely informed by conventional risk assessments may fail to account for these essential services, which could justify the need for additional protective measures.

Result

Overview of WHO guidelines

Norrvatten practices according to WHO Guidelines

The main aim of the WHO guidelines for drinking water quality is to safeguard public health. They offer recommendations to manage risks that could affect the safety of drinking water. Also, to aid in developing risk management plans to guarantee drinking-water safety by regulating harmful elements. These plans might involve setting national or regional standards, and they establish practical safety standards to safeguard consumer health and establish numerical "guideline values" for water components or quality indicators (WHO, 2022). Drinking water suppliers ensure quality through developing water safety plans. However, they typically aren't responsible for managing the catchment areas that supply their water sources. Instead, they collaborate on catchment management to assess contamination risks and work with health and environmental authorities for comprehensive management.

As a result, and after a discussion with Norrvatten experts about fulfilling the WHO guidelines for producing safe drinking water, it was estimated that Norrvatten covers up to 90% and exceeds this percentage of the regulation of the WHO guidelines. This result was conducted using a checklist developed as part of this study to evaluate the water supply's compliance with WHO guidelines. The checklist was created based on the literature review of WHO guidelines. Still, Norrvatten is continuously working on developing its procedures and research for better outcomes of the quality of the produced water and strategies for mitigation of any contaminants that reach the raw water source. The checklist in Appendix 1 (Table 8) shows the WHO regulations for safe drinking water checklist for Norrvatten.

Comparison between WSPs, EU drinking water directive and Swedish legislation

The result of the comparative analysis includes the WSPs, the EU Drinking Water Directive, and Swedish legislation standards. The analysis aims to identify key differences and similarities between these frameworks, focusing on how each approach addresses water safety, risk management, enforceability, and stakeholder involvement, as the analysis shows several shared elements across systems, including a commitment to protecting public health through water quality standards. Key commonalities include approaches to managing emerging risks, engaging stakeholders in decision-making, and balancing strict regulatory enforcement with adaptability to local conditions. The analysis shows that while each system operates within unique regulatory contexts, they converge on essential practices such as risk assessment, preventative measures, and continuous monitoring. These findings illustrate how each framework integrates stakeholder input and adapts to specific regional needs while upholding core health protection goals. After the literature review, a summary table (Table 5) is shown below to differentiate between WHO guidelines for drinking water quality standards and the EU directive legislation.

Table 5. Summary comparison between WHO, EU directive and Swedish legislation for drinking water standards.

Aspect	WHO guidelines for water safety plans (WSPs)	EU drinking water directive	Swedish Legislation for Drinking Water
Scope	Flexible and adaptable; globally applicable with room for local customization.	Rigid and specific to EU member states; focuses on harmonizing standards across the EU.	Based on the EU Directive but adapted to Swedish national conditions and regulations.
Enforceability	Non-binding: implementation depends on national priorities and resources. Voluntary	Legally binding; requires national implementation with penalties for non-compliance. Obligatory	Legally binding; enforced by the Swedish National Food Agency (Livsmedelsverket), with penalties for non-compliance.
Risk-based approach	Risk-based approach and broad WSP framework; adaptable to various risks but may lack specificity Proactive approach	Risk-based approach; sometimes focuses on specific risks and contaminants Reactive approach	Swedish regulations integrate risk-based approaches in line with EU Directive. Emphasize water quality controls and regular risk assessments.
Monitoring and compliance	Emphasizes ongoing monitoring within the WSP framework but lacks enforcement mechanisms.	Requires strict monitoring, more frequent testing, and regular reporting by water suppliers to national authorities.	Water suppliers must conduct regular testing and report to authorities (Livsmedelsverket) according to specified quality standards.
Flexibility	Highly flexible but sensitive to specific context and local conditions.	Limited flexibility due to the legislative nature; harder to adapt to local conditions.	Some flexibility in local adaptations, but compliance with EU standards is prioritized.
Adaptability to emerging risks	Encourages continuous review and adaptation, potentially faster response to emerging risks.	Proactively addresses emerging risks with updates to directives; slower legislative process can delay response.	Swedish regulations adopt EU's approach, including updates for emerging risks, managed through local assessments and national action plans.
Preventive focus	Strong focus on prevention and proactive risk management as a core principle.	Emphasizes compliance with standards, which may sometimes overshadow broader preventive measures.	Strong emphasis on compliance but includes preventive strategies through local oversight and risk mitigation efforts.
Stakeholder involvement	Promotes multi-stakeholder involvement, emphasis on collaboration at local levels.	Involves multiple stakeholders but may centralize decision-making at national levels.	Involves municipalities, water suppliers, and national authorities; localized collaboration.

WSP Global Examples Overview

Global WSP Assessment, Challenges and Variations

Despite the global promotion of WSPs, there is not a comprehensive study on whether risk matrices are accurately constructed to assess risk. For this purpose and in 2023, Lane and Hrudey's study evaluated risk matrices in twelve templates from various global jurisdictions using criteria adapted from previous risk matrix research. These WSP templates are sourced from the WSP Portal website, and definitions of likelihood and impact are extracted from each template for evaluation purposes. The application of detailed mathematical analysis criteria revealed that 11 out of the 12 risk matrices fail to meet at least one of the established criteria.

On the other hand, there is considerable variation in the definitions of likelihood and impact across different jurisdictions, partly due to the system-specific nature of the WSP methodology. To enhance risk matrix construction, Lane and Hrudey recommend setting clearer risk level boundary criteria, aligning impact category definitions with water system objectives, and selecting specific impact categories instead of using multiple definitions. They also suggest that risk matrix construction should be reviewed as part of the WSP process to ensure accurate identification of key risks in water systems. Appendix 2 (Table 9) presents the results of twelve WSPs from around the world, offering a comparison of risk matrix scoring criteria. This includes variations in risk ratings and their definitions. By reviewing these different criteria, this inspires developing our risk matrix that suits all needs.

Lane and Hrudey's study 2023 also discusses the term "qualitatively different risks" or "Poor resolution", which presents a critical evaluation of risk matrices, highlighting the potential for the same risk score to be assigned. This denotes a condition wherein a risk matrix assigns identical risk scores to risk events that differ quantitatively. For instance, a low-probability, high-impact event may receive a risk score of 10 based on a likelihood score of 2 and an impact score of 5. Conversely, a highly probable event with a likelihood score of 5 and a relatively minor impact score of 2 is also assigned a risk score of 10. Despite sharing the same risk score, these events possess quantitative distinctions. The former scenario (low probability, high impact) may represent, for instance, a groundwater contamination event, which, although unlikely, could result in significant adverse human health effects. In contrast, the latter scenario (high probability, low impact) could illustrate the failure of an ageing pump, an event likely due to the pump's age but with minimal impact due to the availability of pumps. Within the water industry, the consequences of a water system failure contain both financial and human health dimensions. The inaccurate characterisation of risk events potentially life-threatening to consumers is dependent on the water system.

The findings of reviewing the twelve WSPs, including the WSP portal standard suggested by the WHO guidelines, show variation in likelihood definitions. The inconsistency in how likelihood is defined across different jurisdictions can significantly affect risk assessment outcomes in WSPs. Moreover, and commonly, a scale of 1-5 is used, but Alberta employs an exponential scale based on powers of 2, while South Africa uses decimals. Likelihood descriptions often refer to specific timeframes, like ‘every 5 years’ or ‘every week’. 'Almost certain' typically means a daily or weekly occurrence. Definitions of 'rare' events differ significantly: Iceland considers an event rare if it happens once every 100 years, whereas other templates (e.g., TECHNEAU manual, Alberta, South Africa) define 'rare' as every 5 years. This inconsistency can lead to underestimating low-probability, high-impact events such as drinking water outbreaks.

Despite the promotion of WSPs worldwide, there are still gaps in accurately assessing risks, making it a key topic for analysing water safety frameworks. The study shows that many jurisdictions struggle with constructing risk matrices that meet established criteria. The variation in definitions of likelihood and impact demonstrates a fundamental issue in standardising WSP approaches across different regions. This indicates that while WSPs are conceptually valuable, their practical implementation can vary in effectiveness. Also, the issue of qualitatively different risks shows how similar risk scores can mask significant differences in risk profiles. Moreover, inconsistent definitions of risk factors like "likelihood" can result in underestimating or overestimating risks, which can lead to improper allocation of resources or unpreparedness for critical events.

For Norrvatten, this analysis suggests that Sweden could benefit from reviewing its matrices for WSPs to ensure consistency in likelihood and impact definitions. Implementing clearer risk criteria could prevent underestimation of low-probability, high-impact events, which are crucial in safeguarding public health. Moreover, distinguishing between different types of risks could help in connecting risk assessment tools and the specific challenges faced by Swedish water systems, such as those posed by local contamination sources or climate-related impacts. Also, aligning likelihood definitions with clear and consistent criteria could improve risk management.

Australia: Lessons from the Sydney Water Crisis

In another study and i990s, the WSP implementation in Melbourne, Australia, started by the recommendations of the Australian Risk Management Guidelines. Australia has developed WSPs, particularly after the Sydney water crisis in 1998. The crisis involved the detection of high levels of pathogens, including Cryptosporidium and Giardia, in Sydney's drinking water supply. This contamination led to a public health scare, with authorities issuing "boil water" alerts for over 3 million residents. The crisis highlighted significant vulnerabilities in Sydney's water management system and prompted a review of water safety practices.

As a result, Australia prioritised the development and implementation of WSPs to enhance the management of drinking water quality and prevent future incidents. The implementation of WSPs across Australian cities, including Melbourne and Brisbane, focused on systematic risk management and the incorporation of HACCP principles. These plans have improved the reliability and safety of the water supply. In Melbourne, metropolitan water utilities began developing systematic drinking water quality management systems. It is noted that the process began in late 1999. Before this, Melbourne’s water utilities relied on monitoring drinking water quality by comparing results against the Australian Drinking Water Guidelines, with a focus on end-point testing (Jayaratne et al., 2023).

This example illustrates how a significant public health crisis led to fundamental changes in water safety management. The learned lessons from Melbourne WSP implementation rely on several key factors: ongoing risk reduction strategies, continuous improvement, and regular audits (Jayaratne et al., 2023). Key strategies include focusing on process improvements and innovative technologies, such as backup systems to mitigate contamination risks within catchment areas and the use of data analytics to monitor and predict potential threats. These approaches enable real-time adjustments to water quality management, enhancing the resilience of Melbourne's water supply system against future public health risks. Continuous improvement involves ongoing risk reviews and learning from incidents to refine processes and stakeholder communication. Regular audits are conducted by skilled compliance officers. Over the past 20 years, Melbourne's WSP has evolved through shared experiences, industry collaboration, and adherence to regulations and practices. This enhances system resilience, preparing Melbourne's water supply for future extreme events (Jayaratne et al., 2023).

Before WSPs, water safety in Australia relied on monitoring and reactive measures, such as issuing public alerts when contamination was detected. There was less focus on proactive risk management, which contributed to the severity of the Sydney crisis. The WSP approach in Australia, particularly after the Sydney water crisis, proved successful in preventing future incidents. By focusing on systematic risk management and the incorporation of Hazard Analysis and Critical Control Points (HACCP) principles, Australia improved the reliability and safety of its water supply. However, the crisis also highlights how reactive management strategies (e.g., boil water alerts) were insufficient to prevent the incident.

The lesson learned from Australia is the importance of moving from reactive to proactive water safety management. Norrvatten could benefit from implementing more robust WSPs that emphasise continuous risk reduction and stakeholder communication.

New Zealand: Reforms Following the Havelock North Incident

New Zealand developed their WSP framework, particularly after the Havelock North incident in 2016, where a major outbreak of campylobacteriosis occurred due to contaminated drinking water. Following this incident, New Zealand implemented reforms to improve its water management practices and prevent future contamination events (Graham et al., 2023 This incident led to significant reforms in New Zealand's water management system. It also exposed major weaknesses in New Zealand's water safety framework, including insufficient monitoring and a lack of risk assessments for potential contamination sources.

As a result of the incident, the New Zealand government established reforms to enhance water safety and prevent future contamination events. One of the main government improvements is the establishment of Taumata Arowai on 1 March 2021. Taumata Arowai is an independent government agency established to regulate water services in New Zealand. It was created in response to the Havelock North water contamination incident. Taumata Arowai is established to oversee drinking water standards across the country. This organisation is responsible for ensuring compliance with new regulations and guidesingater suppliers (Taumata Arowai, 2023). Taumata Arowai requires all water suppliers to develop and maintain Water Safety Plans (WSPs), which emphasise proactive risk management from source to tap. It employs a balanced regulatory approach, encouraging positive changes in the drinking water sector while addressing safety and environmental threats based on health risks, promoting responsibility through guidelines and regulations to prioritise activities based on risk assessment and supporting ongoing improvements in water services (Taumata Arowai, 2023). This strengthened WSP framework is intended to support continuous improvements in water safety and to prioritise high-risk areas using a risk-based approach.

This incident is an example of how a water contamination event can lead to widespread reforms in water safety management. New Zealand's response serves as a model for how countries can overhaul their water management systems following a crisis with a successful shift towards stronger regulatory oversight and proactive risk management. The focus on balancing safety with environmental threats highlights the importance of a holistic approach to water safety. Norrvatten could benefit from enhanced oversight and more stringent risk-based regulation to prevent incidents similar to those in Havelock North.

United Kingdom: Integration of WSPs into Regulatory Framework

The United Kingdom was one of the early adopters of WSPs, and they have been integrated into the regulatory framework through the Drinking Water Inspectorate (DWI). The UK's approach focuses on risk assessment and management throughout the water supply system, from source to tap (DWI, 2023). This has resulted in improved water quality and safety standards across the country. For example, the DWI provides guidelines for PFOS (perfluorooctane sulphonate) and PFOA (perfluorooctanoic acid) concentrations in drinking water. PFOS and PFOA are perfluorinated chemicals that are utilised for various purposes, including as polymer precursors, in specific firefighting foams, and for imparting grease, oil, and water resistance to materials like textiles, carpets, and paper (DWI, 2016). The DWI provides guidelines for PFOS and PFOA concentrations in drinking water at the treatment stage, ensuring that these contaminants are removed or reduced before the water reaches consumers. However, stringent regulations implemented since 2004 in the UK and Europe have significantly limited the permissible uses of PFOS, with very few applications currently allowed.

Before WSPs, water safety management in the UK relied more on compliance with national standards and periodic testing. This example is a valuable example of how WSPs can be successfully integrated into national regulatory frameworks. The UK's focus on risk assessment throughout the water supply system demonstrates the long-term benefits of WSP adoption. For Sweden, the UK example highlights the importance of embedding WSPs into national legislation. Norrvatten could adopt a similar approach by ensuring that water safety plans are not just guidelines but legally mandated frameworks for all water utilities.

Netherlands: Advanced Risk Management Approaches

In the Netherlands, WSPs are integrated into the national water management policy. Dutch water utilities use a comprehensive risk management approach that includes advanced modelling techniques and regular monitoring to ensure water safety by utilising quantitative risk analysis methods like Quantitative Microbial Risk Assessment (QMRA) alongside qualitative approaches such as WSPs. These proactive approaches make the Dutch water supply system one of the safest in the world (KWR Water Research Institute, 2015).

Before the adoption of WSPs, the Netherlands had a strong focus on water management, but it lacked the comprehensive risk-based approach that WSPs offer. This example is chosen because it shows a proactive and advanced approach to water safety management, combining both quantitative and qualitative methods. The Dutch focus on regular monitoring and modelling techniques, making their system one of the safest in the world. It shows the benefits of integrating advanced risk management techniques like Quantitative Microbial Risk Assessment (QMRA). This allows for more precise predictions and better preparation for potential water safety issues. However, implementing such advanced techniques requires significant investment and expertise, which may not be feasible for all regions.

For Norrvatten, adopting advanced risk management approaches like those used in the Netherlands could enhance water safety. Incorporating both qualitative and quantitative methods into Sweden's water safety planning could help address risks more effectively. This approach supports risk assessments that can adapt to emerging threats like climate change, pollution, and urban development.

Canada: Responding to Water Contamination Incidents

While in Canada, the contaminated water incidents in Walkerton, Ontario, and North Battleford, Saskatchewan, prompted provincial governments to take action to enhance drinking water safety. This response included considering legislation aimed at stricter regulations. There's a growing recognition that safeguarding water safety requires not only proper treatment and monitoring but also protecting water sources from pollution, including nonpoint sources (Mallet , 2004).

In another city, Edmonton's handling of the E. coli contamination incident in its water supply in 2001 led to significant improvements in its water safety protocols, water quality and public health protection (Hrudey et al., 2008). The city implemented stricter monitoring and enhanced treatment processes as part of its WSPs, resulting in increased confidence in the safety of its drinking water by developing a WSP that includes stakeholder engagement, regular risk assessments, and continuous improvement practices. This has led to enhanced water quality and public health protection (Mallet, 2004).

Before the adoption of WSPs, Canada's water safety management focused more on treatment and monitoring, with less emphasis on preventing contamination at the source. The Walkerton incident, in particular, revealed the shortcomings of this reactive approach. Canada's experiences with water contamination incidents highlight the importance of stakeholder engagement and continuous improvement in water safety protocols. The adoption of WSPs in response to these incidents led to more proactive risk management and better coordination between government agencies and water utilities.

For Norrvatten, the Canadian experience emphasises the importance of protecting water sources and involving stakeholders in water safety planning. Sweden could enhance its water safety by adopting more stringent regulations that prioritise source protection and continuous risk management.

Pilot Case Study- WSP for Upplands-Bro Municipality

The selected study area is situated in Upplands-Bro municipal area including Brobäcken, Prästtorpsbäcken and Nygårdsbäcken catchments with a total area of 40 149 km2 where Brobäcken catchment is 26 484 km2, Prästtorpsbäcken is 6 215 km2 and Nygårdsbäcken- 7 442 km2. This area is critical since the water from this area flows into Görvälnverkets raw water source, Görväln a part of Lake Mälaren, but is only partially covered by the existing water protection area of the eastern part of Lake Mälaren Östra Mälarens vattenskyddsområde. The fact that the area isn't fully covered by the regulations of the water protection area might allow industries or other potentially harmful activities within the catchment. The studied area of Brobäcken, Prästtorpsbäcken and Nygårdsbäcken is included in the main catchment area for Lake Mälaren named "Norrström". GIS shapefiles data were obtained from open-source data platforms, including SMHI (Swedish Meteorological and Hydrological Institute) and Lantmäteriet (the Swedish Mapping, Cadastral and Land Registration Authority).or were provided from Uppands-Bro municipality to create the following maps presented by the figures below (Figure 3, figure 4, figure 5, figure 6 and figure 7). The study area includes three catchments within the larger Norrström catchment area, which is a key watershed feeding into Lake Mälaren. To analyse these areas, several types of GIS data were obtained Specifically:

- Catchment Area Boundaries and Names: GIS shapefiles containing detailed information on the boundaries and official names of the catchment areas were sourced to outline the geographical scope of each sub-catchment.
- Runoff Data: Runoff values to understand water volume dynamics within the catchments were extracted from SMHI's hydrological datasets.
- River and Stream Flow Lines: GIS shapefiles depicting river and stream networks, including flow directions and connectivity within the study area, were obtained from SMHI. This data was critical in mapping water flow paths that contribute to Norrvatten's raw water sources.

The following map presented in the figure (Figure 3) shows the Lake Mälaren "Norrström" catchment and the location of the study area.

Figure 3. Main catchment area for Mälaren and the study area location (Lantmäteriet, 2024).

The figure (Figure 4) below shows the study area, "Östra Mälarens vattenskyddsområde" water protection area and Norrvatten Görvälnverket drinking water treatment plant. Noting that the Östra Mälarens vattenskyddsområde includes only part of our study area.

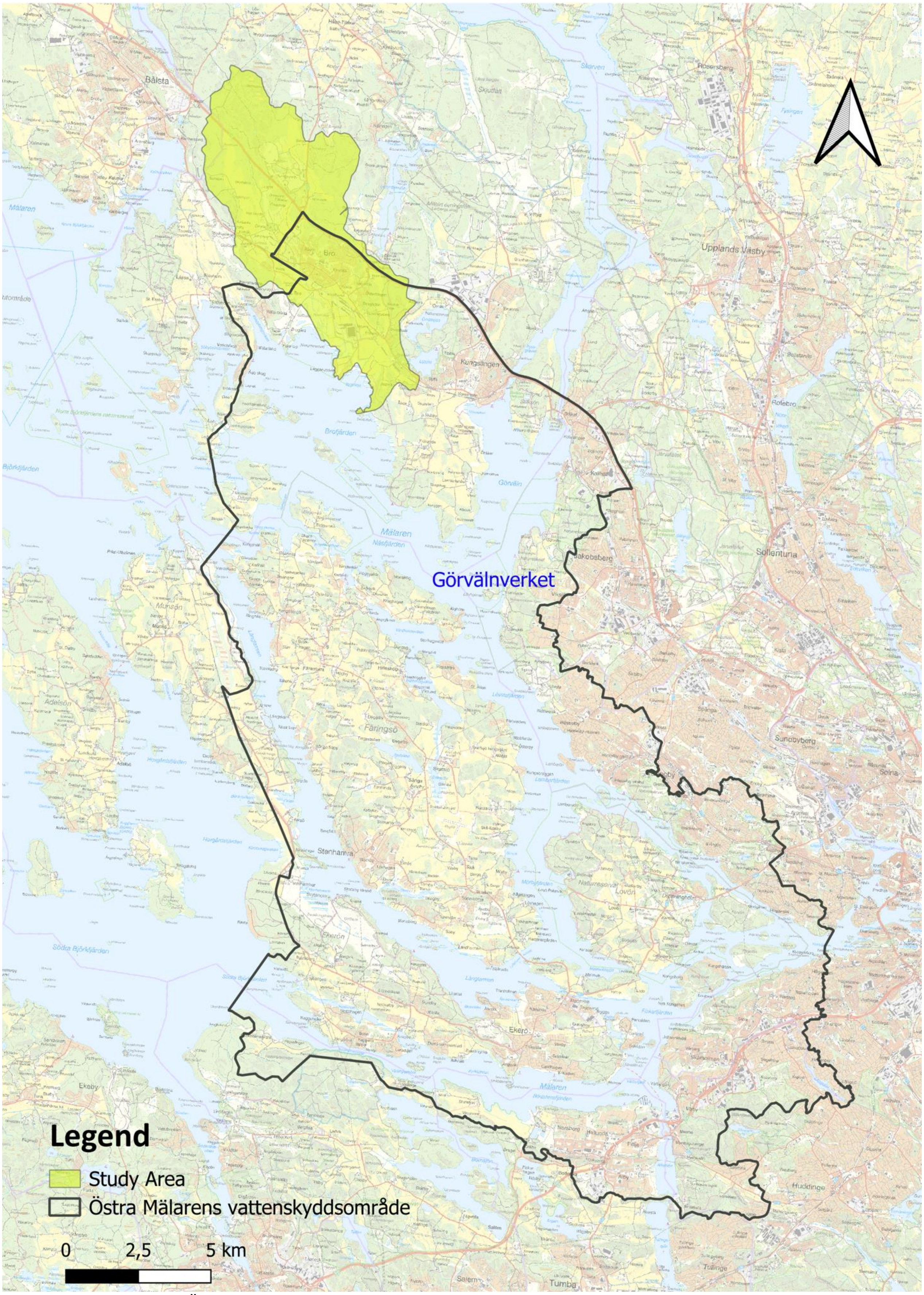

Figure 4. Study area, "Östra Mälarens vattenskyddsområde" water protection area and Görvälnverket (Lantmäteriet, 2024).

Upplands-Bro Municipality is located in Stockholm County in east central Sweden, with its administrative centre in the town of Kungsängen. Situated by Lake Mälaren, Upplands-Bro is known for its attractive nature. The total Population as of 31 December 2023 is 32 453 capita The majority of its population resides in three main towns: Kungsängen, Bro and Brunna (Statistics Sweden, 2023). The rest of the municipality is largely rural, with a significant part of it being agricultural. The study area is characterised by both urban and rural areas. The figure (Figure 5) below shows the Upplands-Bro municipal catchments, including the three catchments Brobäcken, Prästtorpsbäcken, and Nygårdsbäcken studied in this thesis.

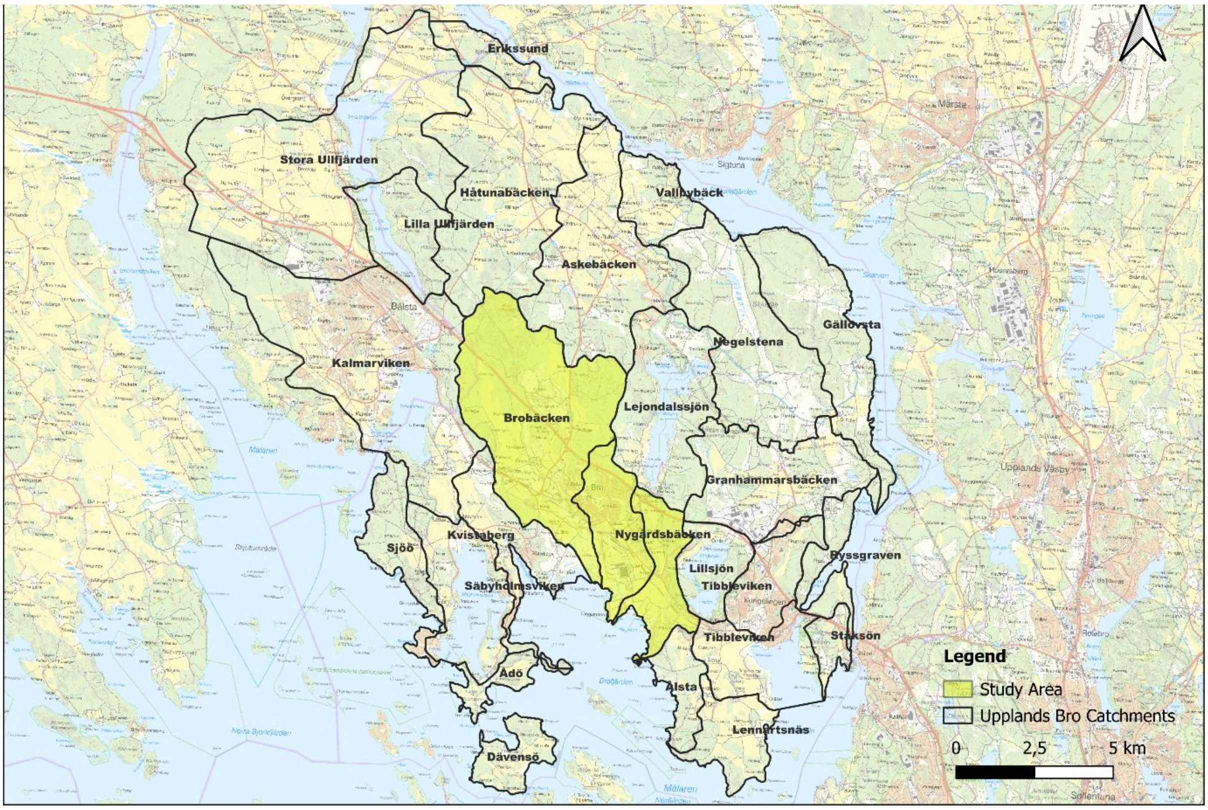

Figure 5. Study area and Upplands-Bro municipal catchments (Lantmäteriet, 2024).

The municipality of Upplands-Bro features substantial rural areas primarily used for agriculture, supporting the local economy and preserving traditional farming. It offers a suburban lifestyle with diverse housing, growing commercial and industrial zones, and recreational options like golf courses, parks, and access to Lake Mälaren for water sports. The area also includes cultural activities, public services, schools, healthcare, railways, and the Högbytorp area with a landfill.

As a result, to evaluate potential hazards for Norrvatten, WHO guidelines for WSPs and a risk matrix were developed to evaluate potential hazards. This semi-quantitative approach involves assessing both the likelihood of occurrence and the severity of consequences for each identified risk source. The matrix utilises a scoring system where probability is rated from 1 (rare) to 5 (almost certain), and severity is rated from 1 (insignificant) to 5 (catastrophic). The final risk score is calculated by multiplying the probability and severity scores.

For the study area's risk evaluation, various potential contamination sources were identified and categorised based on their nature (e.g., industrial areas, landfills, agricultural activities). Each risk source was then assessed for its probability of occurrence and potential severity of impact on water quality. The resulting matrix provides an overview of the risk landscape, allowing for prioritisation of mitigation efforts. Notable high-risk areas identified include the Ragn-Sells Högbytorp waste facility (score: 25), Bro Bålsta landfill (score: 20), and Coop Logistik (score: 20), primarily due to potential heavy metal, PFAS, and chemical contaminations. Agricultural and recreational areas, such as golf clubs, also present significant risks (score: 15) due to pesticides and fertilisers. This risk assessment approach aligns with WHO recommendations, providing a structured method for identifying, evaluating, and prioritising water safety risks in the catchment area. The risk evaluation and scores are shown in the table (Table 6) below.

Table 6. Risk identification, evaluation and scoring for the study area.

Category	Risk type	Likelihood	Severity	Final Score
Stones quarry	Sediments, Heavy metals, Chemical risks	4	2	8
Landfill 1	Heavy metals, PFAS, chemicals	5	4	20
Glassblowing	Heavy metals	2	1	2
Sewage drains 1	Nutrients, microbiological risks	5	1	5
Vehicle services 1	Oil, Tire particulate, brake fluid, battery acid, detergents	2	2	4
Vehicle services 2	Heavy metals, Detergents	3	2	6
Landfill 2	Heavy metals, PFAS, chemicals	5	5	25
Biogas plant	Heavy metals and chemical risks	2	2	4
Energy plant	Polluted ash, Heavy metals	3	3	9
Agriculture, sewage drains	Pesticides, fertilizers, microbiological risks	5	3	15
Urban areas 1	Petroleum risks	2	2	4
Urban areas 2	Petroleum risks	2	2	4
Urban areas 3	Petroleum risks	1	2	2
Industrial areas 1	Chemical risks, Heavy metals	3	3	9
Industrial areas 2	Chemical risks, Heavy metals	1	3	3
Industrial areas 3	Chemical risks	1	3	3
Industrial areas 4	Chemical risks	1	1	1
Farm	Microbiological risks	5	2	10
Recreation area 1	Pesticides, fertilizers	5	3	15
Recreation area 2	Pesticides, fertilizers	5	3	15

Sewage drains 2	Nutrients, microbiological risks	3	1	3
Cemetery	Heavy metals	3	1	3
Recreation area 3	Microplastics	5	2	10
Urban areas 4	Petroleum risks, PFAS, firefighting foam	5	4	20
Vehicle services 3	Petroleum risks, Heavy metals, Chemical risks	3	2	6
Urban areas 5		5	3	15

The figure (Figure 6) shows the result of the evaluation of the risk, with four categories with the most hazardous risk sources as shown with the very high category represented in red circles, orange circles representing a high level of risk, yellow circles representing a medium level of risk and green circles represent a low level of risks. In addition to that, many risks are located outside the "Östra Mälarens vattenskyddsområde" water protection area, as shown on the map. However, contamination risks can flow with the streams, represented by the blue dashed lines. As well, some risk sources are located outside the study area boundary, but they contribute to hazardous contaminations that flow to the study area. In the Upplands Bro, the topography plays a role in groundwater movement. The landscape features both hills and valleys, which influence how water flows. Water typically moves from the higher elevations of the hills down toward the lower areas. In steep regions, water flows quickly, which can lead to rapid transport of contaminants. In contrast, the flatter areas allow for slower groundwater movement and provide opportunities for contaminants to seep deeper into the ground. The valleys in Upplands Bro can collect rainwater and direct it toward the groundwater system. Meanwhile, the surrounding hills can act as barriers, altering the flow patterns of both clean and contaminated water.

This means that if hazardous materials enter the groundwater, their spread may vary based on the local topography. The topography of the Upplands-Bro areas is characterised by rolling hills, valleys, and varying elevations, which influence groundwater movement and drainage patterns. Understanding how the shape of the land interacts with groundwater flow is important for assessing contamination risks in the area as shown in the figure below (Figure 6) for the resulting risk scores.

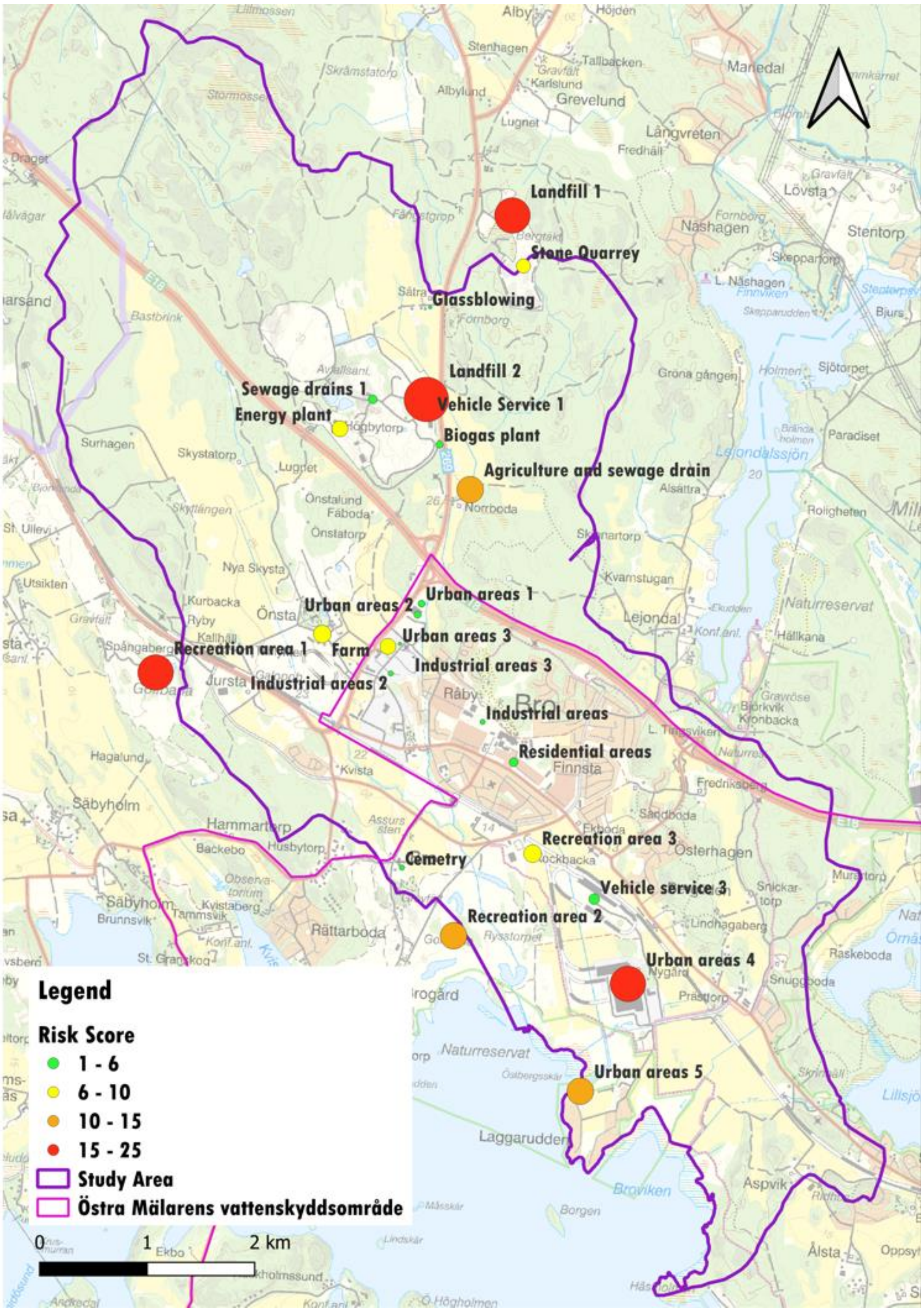

Figure 6. Resulting scores of risk matrix, "Östra Mälarens vattenskyddsområde" and water streams (Lantmäteriet, 2024).

If we zoom out a little, the below map shows how the risk source contaminations can directly affect the raw water source of Norrvatten Görvälnverket with the water streamlines flowing to and reaching Norrvatten's drinking water treatment plant based on the rivers and streams shapefile as shown in the figure (Figure 7) below.

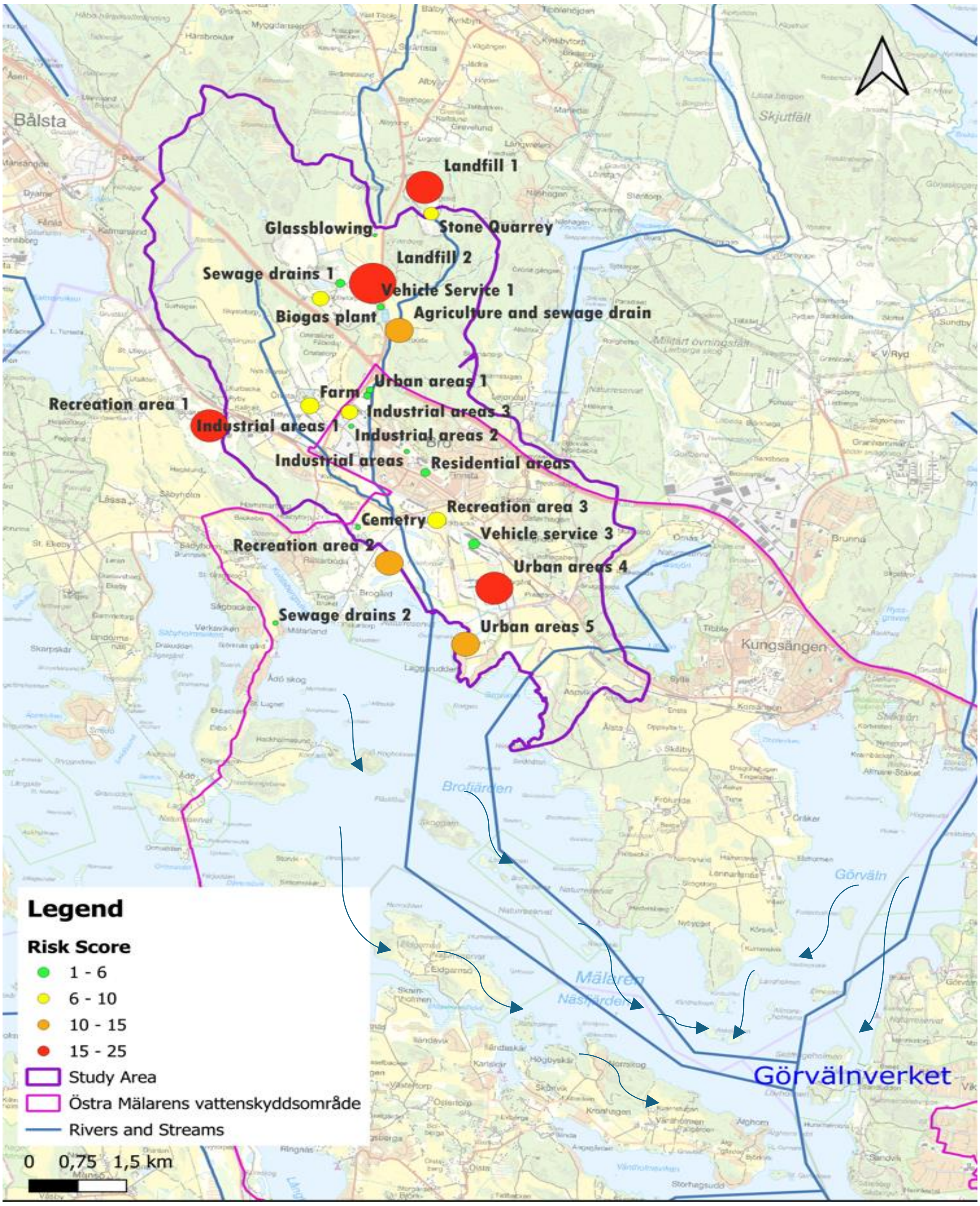

Figure 7: Risks contamination flow lines until raw water source of Norrvatten Görvälnverket (Lantmäteriet, 2024).

Sensitivity in likelihood and severity estimates may be sensitive to small changes in the data or evaluation criteria. For instance, if new data suggests that the likelihood of a contamination event is slightly higher than previously thought, this could alter the overall risk score. When adjusting likelihood or severity scores, some risks may show large variations in their final scores, indicating that they are highly sensitive to changes. This uncertainty can make it challenging to prioritise risks accurately. For example, a small increase in the likelihood of a contamination event could push it from a low-level to a high-level risk, affecting resource allocation decisions. For example, The Bro-Bålsta Golf Club and Bro Hof Castle both have 15 evaluations of the original score, which are considered to be a high-level risk, but with the likelihood-adjusted score and severity-adjusted score, the same risks have 15 and 18 scores, respectively. This pushes the evaluation from a high-level risk to a very high-level risk. The table (Table 7) below shows the different resulting scores with different evaluation methods.

Table 7. Different evaluation scores for risk sources and their variabilities to the original score.

Category	Original score	likelihood-adjusted score	Severity-adjusted score	Variability of likelihood-adjusted score to original score	Variability of severity-adjusted score to original score
Stones quarry	8	10	12	2	4
Landfill 1	20	24	25	4	5
Glassblowing	2	3	4	1	2
Sewage drains 1	5	6	10	1	5
Vehicle services 1	4	6	6	2	2
Vehicle services 2	6	8	9	2	3
Landfill 2	25	30	30	5	5
Biogas plant	4	6	6	2	2
Energy plant	9	12	12	3	3
Agriculture, sewage drains	15	18	20	3	5
Urban areas 1	4	6	6	2	2
Urban areas 2	4	6	6	2	2
Urban areas 3	2	4	3	2	1
Industrial areas 1	9	12	12	3	3
Industrial areas 2	3	6	4	3	1
Industrial areas 3	3	6	4	3	1
Industrial areas 4	1	2	2	1	1
Farm	10	12	15	2	5
Recreation area 1	15	18	20	3	5
Recreation area 2	15	18	20	3	5
Sewage drains 2	3	4	6	1	3
Cemetry	3	4	6	1	3
Recreation area 3	10	12	15	2	5
Urban areas 4	20	24	25	4	5
Vehicle services 3	6	8	9	2	3
Urban areas 5	15	18	20	3	5

The severity of a risk is the most critical estimation since the sensitivity calculation shows that this method led to higher risk scores and is more variable than the original score, as shown in the figure (Figure 8) below that severity-adjusted scores are always higher than the original scores and equal or higher than the likelihood-adjusted scores. The scores are also sorted from low to high variability. The higher the distance is between the adjusted scores and the original scores, the higher the variability magnitude is from the original score, as shown in the figure (Figure 8) below.

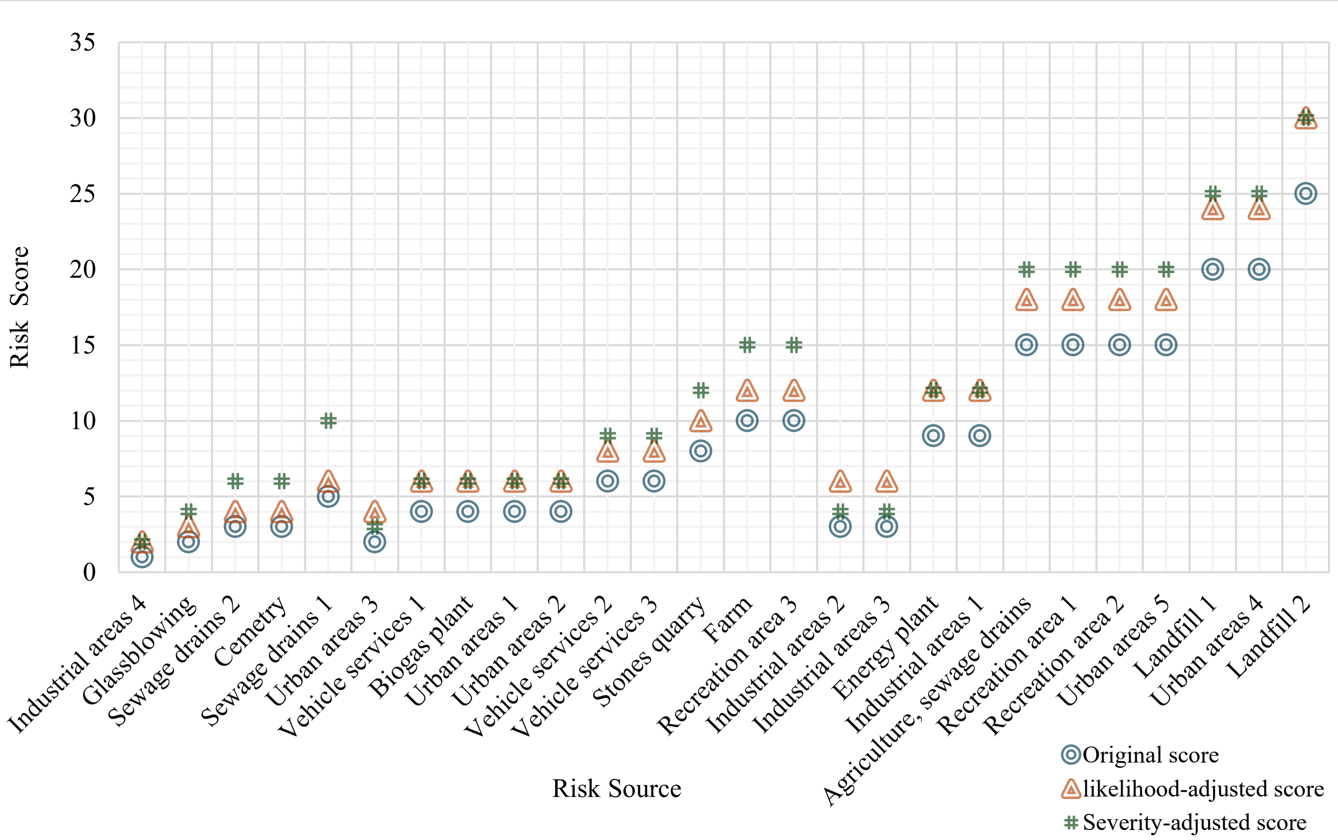

Figure 8. Three methods of risk scoring evaluations.

The figure below shows that the severity-adjusted score method is more variable than the original score compared to the likelihood-adjusted score method since the severity-adjusted score is always higher than the likelihood-adjusted scores as shown in the figure (Figure 9) below.

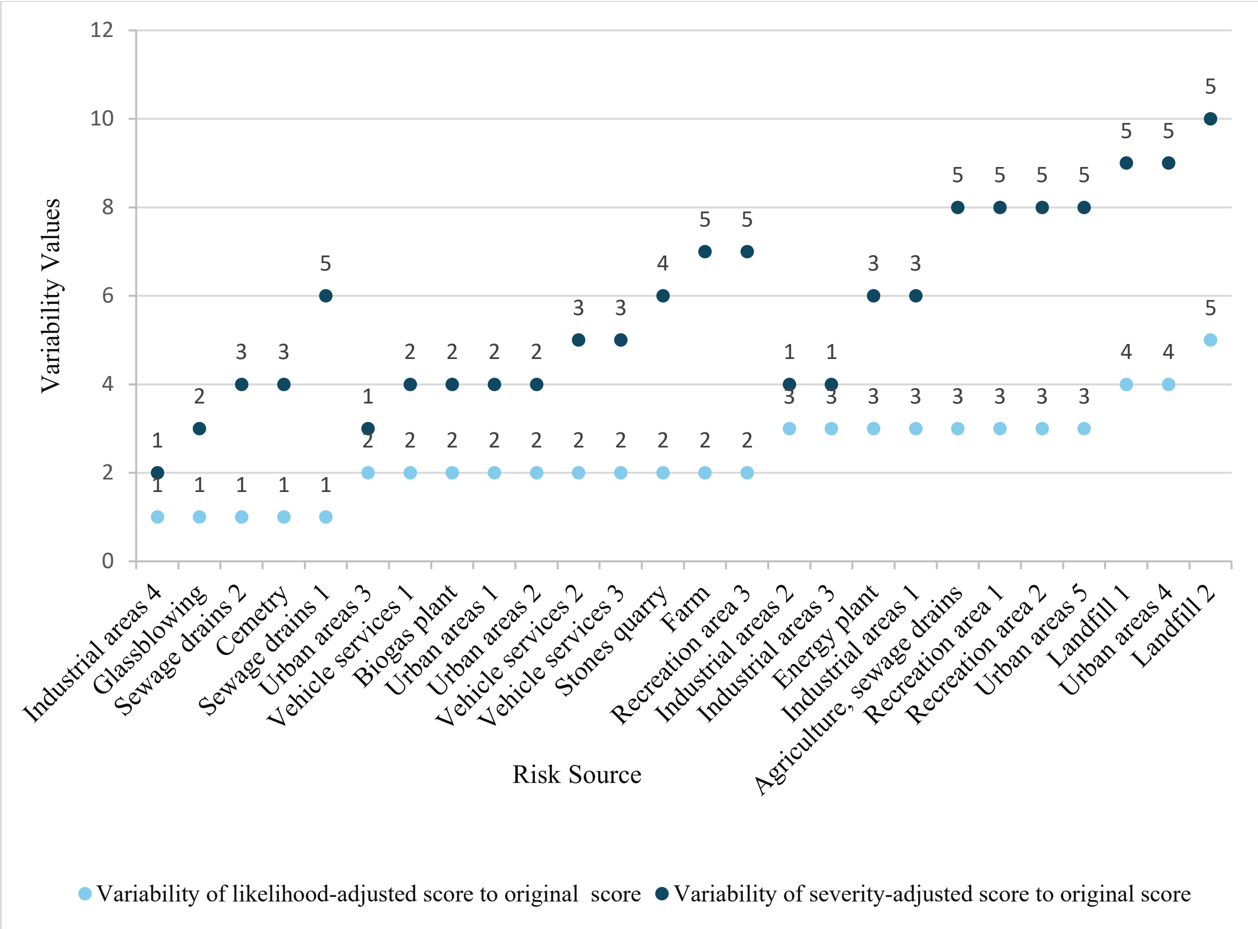

Figure 9. Values of variabilities of likelihood-adjusted score and severity-adjusted score estimations to the original score.

For this risk matrix, several uncertainties can influence the accuracy of the evaluation. Below are key uncertainties that can impact the evaluation of risk matrices: First, data uncertainty leads to imprecise or incomplete data. The quality of data used to assess risk can influence the accuracy of the risk matrix. If the data is outdated, incomplete, or imprecise, it can lead to incorrect estimations of likelihood and severity. For instance, water contamination events could be underreported or incorrectly documented, leading to an underestimation of the likelihood of such events occurring. Also, data gaps are a source of uncertainties. The lack of sufficient data on historical water quality incidents, especially for rare but high-impact events, introduces uncertainty. For example, without sufficient data on the frequency of contamination events due to heavy rainfall, it is challenging to accurately assess the associated risks.

Second, subjective evaluation is related to expert judgment variability. The assessment of risks in WSPs often relies on expert judgment, which can be subjective. Different experts may interpret the same data differently, leading to variations in likelihood and severity ratings. This subjectivity can introduce uncertainty, especially if the criteria for evaluation are not standardised. Additionally, bias in risk perception may be influenced by rational biases, such as overconfidence or the tendency to downplay less understood risks. This can skew the evaluation, resulting in either under- or overestimation of risk levels.

Third, environmental uncertainty is relatively caused by changing environmental conditions. Environmental factors, such as climate change, can introduce uncertainty in the evaluation of risks. For example, increased frequency and intensity of extreme weather events, such as heavy rainfall, can intensify risks that were previously considered low. These changing conditions are not accounted for in this risk matrix. Hence, the evaluation may underestimate the actual risk. Moreover, unpredictable events, such as sudden industrial spills, natural disasters, or accidental contamination. These events may not be fully captured in historical data, leading to an underestimation of their likelihood and severity in risk evaluations.

Fourth, system complexity and interactions, including complex water systems with multiple interdependent components, it can be difficult to accurately assess how risks in one part of the system might influence others. For example, contamination in a source water area might have cascading effects on treatment plants and distribution networks. For instance, the reason for choosing this study area is due to the risks caused by this area to the raw water of the Görväln treatment plant, but these interactions may not be fully captured in the risk matrix. Also, the combined effect of multiple risk factors (e.g., ageing infrastructure and increased pollution) can increase overall risk, but these cumulative effects may be difficult to quantify and incorporate into the risk matrix as further investigation is needed.

Fifth temporal uncertainty, like seasonal variability. Risk levels may vary with seasons, such as increased contamination risks during rainy seasons or droughts, but the risk matrix may not account for these temporal fluctuations. The evaluation is based on a static assessment rather than dynamic conditions; this can lead to inaccurate conclusions. Moreover, changes over time, risks can evolve due to factors such as urban development, industrial activities, or new sources of pollution since more expansion is expected in this area. Without regular updates to the risk matrix, the evaluation may not reflect the current risk landscape. Finally, measurement and model uncertainty, like the mathematical models used to calculate risk scores, are based on assumptions that may not fully capture the complexity of real-world scenarios. In this study, our mathematical model simplifies the evaluation process and certain factors or may fail to account for all relevant variables like vulnerability for example, the resulting risk scores may be inaccurate.

Discussion

Regulatory Compliance and WSP Implementation

This study examines Norrvatten's water quality management practices about WHO, guidelines directives and Swedish legislation. The analysis reveals that Norrvatten meets EU and Swedish regulatory standards, with its practices aligning with approximately 90% of WHO guidelines. This high level of compliance shows it is not a necessity for Norrvatten to implement a WSP to manage their practices for providing water safety and adhering to the quality of drinking water standards, though it also provides a strong foundation for potential WSP implementation. This aligns with the findings of other studies. For instance, Gunnarsdottir's study in 2012 observed improvements in water quality compliance following WSP implementation in Iceland, including a 14% reduction in heterotrophic plate counts, which is a method that measures colony formation on culture media of heterotrophic bacteria in drinking water, and a 41% reduction in diarrheal incidence. Such findings underscore the potential benefits of WSP implementation, even in systems already meeting regulatory standards.

Despite Norrvatten's high level of compliance, our analysis identifies areas for improvement, particularly in formalising WSP procedures and enhancing systematic risk assessment across the entire water supply chain. This aligns with the findings of Roeger and Tavares (2018), who emphasised the need for continuous improvement in WSP implementation, even in advanced water management systems. Their research highlighted that regular reviews and updates are essential for maintaining WSP effectiveness, a finding directly applicable to Norrvatten's context.

Advantages of WSP Implementation

The implementation of a WSP, as recommended by the WHO, offers several advantages. First, it provides a risk management strategy that can identify and mitigate hazards not fully addressed by current legal standards. This proactive approach focuses on early risk identification and the implementation of preventive measures, potentially averting issues before they arise. WSPs also offer greater adaptability, allowing water management systems to accommodate changes in environmental conditions, infrastructure, and technology. This flexibility is particularly valuable in the face of emerging challenges such as climate change and rapid urbanisation.

Furthermore, while not a legal requirement, WSP implementation can support regulatory compliance by providing a structured approach to monitoring and managing water quality. It can help identify areas where additional measures may be needed to meet or exceed regulatory standards. Emergency preparedness is another key benefit of WSP implementation. By including planning for natural disasters or contamination events, WSPs can enhance a water supplier's ability to respond effectively to crises, minimising potential impacts on water quality and public health.

From an operational perspective, WSPs can lead to resource optimisation. By identifying and addressing risks systematically, efforts and investments can be focused on the most critical areas for water safety, potentially leading to more cost-effective management of water supplies. Lastly, implementing a WSP can build stakeholder confidence by demonstrating a commitment to water safety that goes beyond mere compliance. This proactive approach can enhance trust among consumers, regulators, and other stakeholders.

The EU directive and Swedish legislation effectively align the requirements for safe drinking water, establishing a comprehensive framework that is sufficient to ensure high standards of water quality. In Sweden, with its advanced infrastructure and stringent regulations, the need for Water Safety Plans (WSP) is less critical compared to countries where legislative measures may be lacking or where water suppliers face fewer requirements and standards. WSPs serve as a valuable approach in such contexts, notably in nations like New Zealand and Australia, where they have been successfully implemented to enhance water safety. However, in Sweden—a developed country recognised for its high standards in water safety—existing regulations adequately address the challenges of water quality management, minimising the necessity for supplementary WSP frameworks. Nevertheless, this study is an opportunity for Norrvatten to enhance its approach by addressing potential gaps. Focusing on developing more proactive measures rather than reactive responses can significantly improve water management practices. This includes incorporating adaptability strategies to account for challenges such as climate change and enhancing emergency preparedness. By emphasising these proactive measures, Norrvatten can contribute to a more resilient water supply system that not only meets regulatory requirements but also anticipates and mitigates future risks.

Comparative Analysis: WSP, EU Directive and Swedish Legislations

This study also presents s a detailed comparison between WSP implementation and adherence to EU directives and Swedish legislation; it reveals several key differences in approach. The EU directive primarily focuses on ensuring compliance with specific legal standards, adopting a more reactive stance to water quality management. In contrast, the WSP approach is inherently proactive, emphasising the management of safety throughout the entire water supply system. The legal status of these approaches also differs significantly. EU directives are mandatory and require incorporation into national legal frameworks, with specific deadlines for implementation and mechanisms for enforcement. WSPs, on the other hand, are voluntary and adaptable, designed as tools for water suppliers and public health authorities to systematically improve water safety without specific legal obligations.

The scope of risk assessment also varies slightly between the two approaches. The EU directive's risk assessment primarily focuses on ensuring compliance with specific water quality parameters. It emphasises the identification and management of risks that could lead to non-compliance with established standards for contaminants and quality. This approach may be less flexible in adapting to local conditions and emerging risks. In contrast, WSPs take a broader approach to risk assessment, examining the entire water supply system from source to tap. This includes identifying hazards, assessing risks, and implementing control measures for all potential threats, not just those related to regulatory parameters. Moreover, WSPs integrate risk assessment with operational procedures, staff training, and community engagement, fostering a culture of safety and continuous improvement. This holistic approach allows for greater flexibility in addressing local challenges and emerging risks.

In addition to these frameworks, Sweden employs practices for water protection areas and incorporates HACCP principles in its water management. Water protection areas help safeguard sources of drinking water from contamination, while HACCP provides a systematic method for identifying and controlling potential hazards throughout the water supply process. Together, these initiatives complement existing regulations and further enhance the overall safety and sustainability of Sweden's drinking water systems.

Water Protection Area Mismatch with The Study Area

A significant finding of this study is the mismatch between the designated water protection area and the actual catchment contributing to Norrvatten's water supply. This issue, where administrative boundaries fail to align with the actual risk area that drains into raw water sources, has been observed in other contexts. Gerner et al. (2018) highlighted similar challenges in delineating protection zones for groundwater resources in Germany, noting that misaligned boundaries could lead to inadequate protection of recharge areas. These findings align with Hrudey et al. (2006), who emphasised the importance of source water protection as a first step in a multi-barrier approach to drinking water safety. A multi-barrier approach involves implementing multiple strategies and safeguards at different stages to ensure the safety and quality of drinking water. This method recognises that relying on a single barrier—such as treatment—may not be sufficient to protect water quality. Instead, it integrates various measures, including source protection, treatment processes, distribution system management, and monitoring. By addressing potential risks at each stage, the approach helps create a more reliable system for safeguarding public health. They argued that administrative boundaries often fail to reflect the actual areas influencing water quality, potentially leaving critical areas unprotected.

Hydrological realities refer to the actual natural processes and characteristics of water movement and distribution in a given area. These include factors such as groundwater flow, surface water drainage, and the interactions between different water bodies. For example, in the Upplands Bro areas, rainwater that falls on higher elevations may flow into different catchments than those outlined by administrative boundaries. If a designated water protection area is effectively covering the area, it may not encompass the entire catchment area from which Norrvatten draws its water. As a result, contaminants from areas outside the protection zone can easily reach the water supply, compromising its quality. Another example can be seen in the presence of streams and rivers that may cross administrative lines. If a stream that feeds into Norrvatten’s supply is located outside the designated protection area, any pollution upstream may not be adequately managed, putting the water quality at risk. Thus, recognising these hydrological realities is essential for effective water management and protection strategies."

The mismatch between designated water protection areas and actual catchments poses significant risks for Norrvatten, as it compromises the effectiveness of water quality management strategies. This misalignment can contribute to the replenishment of water resources, increasing the risk of contamination from surrounding land use practices. When protective measures do not encompass the true source areas, there is a heightened potential for pollutants, such as nutrients from agricultural runoff or pathogens from urban wastewater, to infiltrate the water supply. Additionally, this oversight can result in a false sense of security, where stakeholders believe that water resources are adequately protected, potentially delaying necessary interventions and increasing vulnerability to contamination events.

Furthermore, the lack of alignment between administrative and hydrological boundaries can complicate coordination among various stakeholders, hindering collaborative efforts to implement comprehensive protection strategies. This gap in alignment between administrative and hydrological boundaries in water protection areas is not widely addressed in current WSP literature. Our study thus contributes insights highlighting an often-overlooked aspect of water resource management that could impact the effectiveness of WSPs in the study area, underscoring the urgent need for policies that better reflect hydrological realities to ensure the safety and sustainability of drinking water resources.

Study Area Risks Evaluation and Risk Matrix Methodology

The case study employed a risk matrix with a hazard identification process, utilising databases and land use data. This approach aligns with recommendations by Bartram et al. (2009) for risk assessment in WSPs, which emphasises the importance of considering all potential hazards from catchment to consumer. Our risk assessment matrix provided insights into raw water risk sources and the complex interplay between hazards and water system services, a complexity also noted by Schijven et al. (2015) in their quantitative microbial risk assessment studies. For instance, they found that the risk of infection from Cryptosporidium could vary by several orders of magnitude depending on the specific characteristics of the water system and treatment processes.

Global Perspectives on WSP Implementation

Examining global examples provided insights into best practices and common challenges. In Australia, Jayaratne et al. (2023) reported on the successful implementation of WSPs in Melbourne, highlighting the importance of continuous improvement and regular audits. They noted that over 20 years, Melbourne's water quality incidents reduced significantly, with a 70% decrease in customer complaints about water quality. In New Zealand, Graham et al. (2023) discussed the reforms in water safety management following the Havelock North water contamination incident in 2016, which led to the establishment of Taumata Arowai, a dedicated water services regulator. The UK's approach, as described by the Drinking Water Inspectorate (DWI, 2023), emphasises the integration of WSPs into the regulatory framework, leading to improved compliance with water quality standards across the country.

These experiences emphasise the importance of continuous improvement, stakeholder engagement, and regular audits in maintaining effective WSPs. These findings align with those of Summerill et al. (2010) on the role of organisational culture in WSP implementation. They found that leadership commitment, open communication, and a proactive approach to risk management were key factors in successful WSP implementation.

Challenges and Future Research Directions

The study identified several challenges in implementing WSPs, including the need for a holistic approach to water resource management, adaptation to local contexts, and improved data collection and analysis capabilities. These challenges are consistent with those identified by Omar et al. (2017) in their study of WSP implementation in developing countries, where they noted that cultural factors and local governance structures significantly influenced WSP success. Collaboration with multiple stakeholders emerged as crucial for managing risks in the catchment area, a finding supported by Rondi et al. (2015) in their analysis of WSP implementation in small communities in Italy. They found that engaging local authorities, farmers, and industry representatives led to more comprehensive risk assessments and more effective mitigation strategies. While this study provides valuable insights, several limitations and areas for future research have been identified. These include the need for longitudinal studies to assess the long-term impacts of WSP implementation, more robust economic valuation of ecosystem services within the WSP framework (building on the work of Gärtner et al., 2022), and detailed research on climate change adaptation in WSPs (extending the work of Hoque et al., 2012).

Future research could also explore WSP implementation in the study catchment area, similar to the work done by Rondi et al. (2015) in Italy and investigate the integration of emerging technologies such as AI and IoT in WSP implementation and monitoring. IoT devices can provide real-time data on water quality, allowing for immediate detection of contaminants. AI can analyse this data to predict potential issues and optimise resource allocation. Together, these technologies can improve decision-making and enhance the overall effectiveness of WSPs, ensuring safer water supplies. Additionally, analysis of stakeholder engagement strategies specific to the Swedish context could provide valuable insights for tailoring WSP approaches to local conditions. The implementation of a WSP for Norrvatten presents both challenges and opportunities for enhancing water safety, improving operational efficiency, and building public trust. As global challenges such as climate change and urbanisation continue to impact water resources, the proactive approach represented in WSPs becomes increasingly crucial.

Conclusions

This study has provided an analysis of water safety management practices at Norrvatten, focusing on the Upplands-Bro municipality catchment area. A key finding of our research is that Norrvatten currently fulfils the European Drinking Water Directive's standards and adheres to more than 90% of the World Health Organization's guidelines and recommendations. This high level of compliance indicates that the implementation of a WSP is not a necessity for Norrvatten from a regulatory standpoint.

However, our investigation reveals that while WSP implementation is not mandatory for Norrvatten, it presents a strategic choice that could further enhance Norrvatten's water safety standards. The adoption of a WSP framework offers potential benefits in terms of risk management, operational efficiency, and stakeholder confidence, which go beyond mere regulatory compliance. The study underscores the transformative potential of WSPs in shifting water management paradigms from reactive to proactive approaches. For an organisation like Norrvatten, already performing at a high standard, WSP implementation could serve as a tool for continuous improvement and excellence in water safety practices. Implementing a WSP could fill the gaps left by the HACCP method in managing Norrvatten's water quality. WSPs offer future risk management by addressing broader threats, such as climate change and urbanisation. WSPs are updated more frequently than HACCP, these regular updates ensure continuous improvement, boosting both efficiency and stakeholder confidence. Additionally, WSP allows for advanced risk assessment tools like Quantitative Microbial Risk Assessment (QMRA) and risk matrices to identify and mitigate potential risks.

A significant insight from this research is the critical need for alignment between administrative boundaries and hydrological realities in water protection strategies. This misalignment represents a challenge that, if addressed through a WSP approach, could substantially improve the effectiveness of water safety measures. Specifically, Norrvatten faces a notable problem in that the designated water protection area does not encompass the entire catchment, leading to the potential oversight of various risks. The Upplands-Bro study, with its risk evaluation, serves as an example of how critical areas may be left unassessed, thus failing to capture the full spectrum of threats to water safety. Additionally, there may be even more risks that warrant evaluation further upstream in the upstream catchment, which have not been adequately considered in the current framework.

Global experiences with WSPs show that inconsistent risk criteria can prevent effective water safety management. For Norrvatten, refining its risk matrix definitions—especially around likelihood and severity—can help address critical, low-probability events and protect public health. Adopting lessons from other developed countries like Australia, the UK, New Zealand, Canada, and the Netherlands, Norrvatten can improve its approach by ensuring continuous updates, clear risk boundaries, stakeholder engagement and integrating both qualitative and quantitative methods in risk assessment.

In conclusion, this study confirms that Norrvatten's current practices are sufficient from a regulatory perspective. However, it also lays the groundwork for potential enhancements in water safety management. By considering the principles of WSPs, Norrvatten has the opportunity to build upon their strong foundation and potentially set new benchmarks for water safety and environmental stewardship. If the WSP approach were to be implemented, it could facilitate a more effective evaluation of risks, including those that currently remain unidentified, thus enriching the overall safety and sustainability of the water supply. In our case study, Upplands-Bro municipality conducted site visits, documented potential sources of risk through photographs and shared their findings with us for further analysis. This proactive strategy would not only enhance the understanding of existing threats but also emphasise the importance of municipalities and other authorities in actively monitoring, investigating, and addressing potential threats to water quality. By fostering collaboration among stakeholders, the WSP framework could push these entities to take more decisive action in mitigating risks, ultimately leading to enhanced protection of water resources.

The path forward for Norrvatten and similar organisations involves weighing the benefits of WSP implementation against their current practices. As global challenges such as climate change and urbanisation intensify, the proactive, risk-based approach embodied in WSPs may become increasingly valuable, even for high-performing water providers. Sweden, with its strong foundation in water management, is well-positioned to explore these advanced approaches, potentially setting new standards for water safety in the 21st century.

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Appendix 1: Checklist for Water Suppliers Adherence to WHO Guidelines

Table 8. Checklist for Norrvatten adherence to WHO guidelines for safe drinking water.

<table>
<tr><th colspan="9">Checklist for Norrvatten Adherence to WHO Guidelines for Safe Drinking Water</th></tr>
<tr><td rowspan="6">1. Framework for safe drinking water</td><td rowspan="2">Fulfil national legislations for water, health and local governance- Water Framework Directive</td><td rowspan="2">Microbial aspect</td><td rowspan="2">Chemical aspect</td><td rowspan="2">Radiological aspect</td><td rowspan="2">Disinfection</td><td colspan="3">Accessibility aspect</td></tr>
<tr><td>Taste ✗✓</td><td>Odor ✗✓</td><td>Appearance ✗✓</td></tr>
<tr><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Fulfil Swedish legislations- Swedish Food Agency</td><td rowspan="2">Microbial aspect</td><td rowspan="2">Chemical aspect</td><td rowspan="2">Radiological aspect</td><td rowspan="2">Disinfection</td><td colspan="3">Accessibility aspect</td></tr>
<tr><td>Taste ✗✓</td><td>Odor ✗✓</td><td>Appearance ✗✓</td></tr>
<tr><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">2. Surveillance and quality control- Jarfalla Kommun</td><td>Meet targets and obligations</td><td colspan="4">Periodic audits for all aspect of saftey of drinking water</td><td colspan="3">Verifications and testing</td></tr>
<tr><td>✗✓</td><td colspan="4">✗✓</td><td colspan="3">✗✓</td></tr>
</table>

Water Resource Management: Detect risks resources from	Industries	Mining	Military sites	Recreation	Urban/ Rural residential development, waste disposal, sanitation and landfill	Land cover modification	Construction/ Modification of waterways	Application of fertilizers, herbicides, pesticides and other chemicals	Livestock density and application of manure	Road construction maintenance and use	Extraction activities
	×√	×√	×√	×√	×√	×√	×√	×√	×√	×√	×√
Certification agencies	Process	Collection	Treatment	Storage	Products: pumps, etc		Material such as treatment chemical		Devices	WSP	
	×√	×√	×√	×√	×√		×√		×√	×√	
Plumbing	Delivery of water complies standards				×√						
Water vendors	Good treatment of vended drinking water for households at collection points				×√						
Community Management	Increase community awareness and knowledge of drinking water quality issues				×√						
3. Water Safety Plan	×√										
Risk Assessment	×√										

<table>
<tr><td rowspan="2">System Assessment: Does drinking water supply meet:</td><td>Health-based targets</td><td>Water-quality targets</td><td colspan="2">Performance target</td><td colspan="3">Specified technology target (e.g application of treatment process)</td><td colspan="2">Address challenges like climate change</td><td>Demographic changes: urbanization</td></tr>
<tr><td>✗✓</td><td>✗✓</td><td colspan="2">✗✓</td><td colspan="3">✗✓</td><td colspan="2">✗✓</td><td>✗✓</td></tr>
<tr><td rowspan="2">Operational Monitoring</td><td>Critical Control Measures</td><td>Observations</td><td>parameters</td><td>Turbidity</td><td>Chlorine residual</td><td colspan="2">Structural integrity: Control on faults, allow leakage and permit the entry of contaminants</td><td colspan="3">Definition of operational limits</td></tr>
<tr><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td colspan="4">✗✓</td></tr>
<tr><td rowspan="2">Tests</td><td>Determination sampling locations</td><td>sampling methods</td><td>Sampling schedule and frequencies</td><td>Procedures for checking results</td><td>Certification required for testing laboratories</td><td colspan="2">Methods for ensuring quality assurance and validation of sampling results.</td><td colspan="2">Inclusion of corrective action procedures with assigned responsibilities</td><td>Staff responsibility and qualifications</td></tr>
<tr><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td colspan="2">✗✓</td><td colspan="2">✗✓</td><td>✗✓</td></tr>
<tr><td rowspan="2">Management Plans: Procedures during</td><td>Normal operation</td><td>Incidents</td><td>Emergency</td><td>Optimal operations</td><td>Establishing working groups</td><td>Task forces</td><td>Committees</td><td>Representatives</td><td colspan="2">Develop partnerships</td></tr>
<tr><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td>✗✓</td><td colspan="2">✗✓</td></tr>
</table>

Incidents and emergency	Staff readiness	Learned lessons	Clear action descriptions for alert levels	Response procedures	Measurable indicators and trigger values for incidents	Logistical and technical information	Checklists and quick reference guides	Accountabilities, contact details of key personnel/ organizations	Location for standard operating procedures and equipment	backup equipment locations
	×√	×√	×√	×√	×√	×√	×√	×√	×√	×√
Post-incidents investigations:	Cause	Problem	Recognition	actions	communications	Effectiveness	Consequences	Response Plan functionality		
	×√	×√	×√	×√	×√	×√	×√	×√		
Communications	Notification procedures for significant incidents		Inform public health authority when needed		Provide summary information annual reports			Online platform	Mechanisms to receive and promptly address community complaints	
	×√		×√		×√			×√	×√	
Revision and Development	Periodic review and revision of standards				Add new parameters based on risk assessment justification		Supporting program	Training programs	Personnel educational programs	Research
	×√				×√		×√	×√	×√	×√
Documentation	Flow Diagrams	Control measures	Operational monitoring	Verification on Plans	Performance consistency	Evaluating results	Management procedures	Incidents	Potential hazards and hazardous events	
	×√	×√	×√	×√	×√	×√	×√	×√	×√	
	Reporting	Performance Evaluations	Audits	Reviews	Communication protocols	Community consultation		Plans for improvements		Emergency response plan
	×√	×√	×√	×√	×√	×√		×√		×√
	Developed to ensure that current versions are in use and obsolete documents are discarded							×√		

	Assembled in a manner that enables any necessary modifications to be made easily	✗✓
	Documentation and records systems kept simple and focused as possible	✗✓
	Reviewed and revised periodically	✗✓

Appendix 2: Comparison Between Risk Matrix Criteria

Table 9. Comparison between risk matrix criteria (Lane and Hrudey, 2023).

Risk matrix	Likelihood			Consequence		
	Score	**Definition**	**Description**	**Score**	**Definition**	**Description**
WHO WSP Manual	1	Rare	Once every 5 years	1	No impact	Insignificant
	2	Unlikely	Once a year	2	Minor	Minor complianc impact
	3	Moderate	Once a month	3	Moderate	moderate aesthe impact
	4	Likely	Once a week	4	Major	Major regulatory impact
	5	Almost certain	Once a day	5	Catastrophi c	Catastrophic Puk health impact
Iceland	1	Very little	Once in 100 years	1	Very little	_
	2	Little	Once in 10-100 years	2	Little	_
	3	Average	Once 1-10 years	3	Average	_
	4	High	Once a year to once a week	4	High	_
	5	Very high	More than once a year	5	Very high	_
Ireland	1	Most unlikely	Has not happened in past and is highly improbable to happen in future	1	Insignifican t	No health impac
	2	Unlikely	Has happened in past and is possible to happen, cannot be ruled out completely	2	Minor	Short-term or localized, aesthe or not health related
	3	Foreseeable	Has happened in past and is possible to happen, and under certain circumstance	3	Moderate	Long-term non-compliance, widespread aesthetic issues

			s could happen again			
	4	Likely	Has occurred in past more than once, is likely to happen again	4	Major	Potential long-term health effects, disruption to consumers in the supply.
	5	Almost certain	Has occurred in past, is an ongoing problem, and is very likely to happen again	5	Catastrophic	Presence of microorganisms, parasites, or substances that are an imminent danger to public health Treatment compromised. Regulatory failure. Disruption to consumers in the supply.
TECHNEAU	NA	Rare	Once every 5 years	1	Insignificant	No impact
	NA	Unlikely	Once a year	2	Minor	Minor aesthetic impact
	NA	Moderately Likely	Once a month	4	Moderate	Major aesthetic impact
	NA	Likely	Once a week	8	Major	Morbidity
	NA	Almost certain	Once a day	16	Catastrophic	Mortality
Alberta	0	Not applicable	Not applicable	0	Not applicable	Not applicable
	1	Most unlikely	small chance in 4-5 years	1	Insignificant	Water meets appropriate standards or system interruption lasted less than 8h
	2	Unlikely	Possible, cannot be ruled out in 4-5 years	2	Minor	Short-term or localized non-compliance, not health related, or system interruption lasted 8–12 h

	4	Medium	Equally likely, not expected to happen in 4-5 years	4	Moderate	Widespread or long-term non-compliance, not health related, or system interruption lasted 12–24 h
	8	Probable	Expected to happen in 4-5 years	8	Severe	Potential illness or system interruption 24–48 h
	16	Almost certain	Will happen at least once in 4-5 years	16	Catastrophic	Actual illness, potential long-term health effects or system interruption more than 48 h
South Africa	0.1	Rare	Once in 5 years	1	Insignificant	No impact
	0.2	Unlikely	Once a year	2	Minor	Small aesthetic impact
	0.5	Moderately	Once a month	20	Moderate	Large aesthetic impact
	0.8	Likely	Once a week	70	Major	Population exposed to significant illness
	1	Almost certain	Once a day or permanent	100	Catastrophic	Death expected from exposure
Pacific Islands	1	Uncommon not likely to occur	Very uncommon	1		No potential to harm public
	2	Event may not occur	Event may not occur	2		Minor irritation or discomfort
	3	Event could occur	Event could occur	3		Potential to cause illness
	4	Event happened before and likely to happen again	Event happened before and likely to happen again	4		Potential to cause illness and hospitalization of a community
	5	Almost certain	Very common,	5		Potential for deaths within a community

			occur on a regular basis			
Malaysia	1	Rare	Every decade	1	Insignificant	Not detectable
	2	Unlikely	Yearly	2	Minor	Requirements compliance
	3	Possible	Monthly	3	Moderate	Compliance aesthetic
	4	Likely	Weekly	4	Major	Compliance with laws
	5	Almost certain	Daily	5	Catastrophic	Public health compliance
Bhutan	1	Could occur at some time but it is not observed		1	Minor impact	Minor or negligible impact
	2	Might occur at some time, has been observed occasionally		2	Moderate impact	Minor impact on water quantity or quality
	3	Will probably occur, has been observed regularly		3	Major impact	Major quantity or quality impact, illness in community
Nepal	1	Unlikely	Could occur, never been observed and may occur in exceptional circumstances	1	Minor impact	Minor or negligible impact
	2	Possible	Might occur, has been occurred occasionally	2	Moderate impact	Minor water quality impact
	3	Likely	will probably occur in most circumstances, has been observed regularly	3	Major impact	Major water quantity or quality impact
Australian Dirking Water Guidelines	E	Rare	May occur in exceptional circumstances	1	Insignificant	little disruption, normal operation
	D	Unlikely	Could occur at some time	2	Minor	Minor impact of small

						population, some manageable operation disruption
	C	Possible	Might occur or should occur	3	Moderate	Minor impact of large population, some manageable operation disruption
	B	Likely	Will probably occur in most circumstances	4	Major	Major impact, system modifications needed but manageable
	A	Almost certain	Will probably occur in most circumstances	5	Catastrophic	Major impact for large population, complete failure of systems
New Zealand	Rare	May occur only in exceptional circumstances, once in 1000 years		Insignificant	Insignificant	Insignificant
	Unlikely	Could occur once in 100 years		Minor	Minor	Minor impact for small population
	Possible	Might occur, once in 10 years		Moderate	Moderate	Minor impact for big population
	Likely	Will probably occur once in 1-2 years		Major	Major	Major impact for small population
	Almost certain	Is expected to occur in most circumstances		Catastrophic	Catastrophic	Major impact for big population

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