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Evaluation of storm- and rainwater recycling systems in Scandinavia

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Abstract

This study examined the current state of storm- and rainwater recycling for non-potable purposes, like the flushing of toilets, in Scandinavia as well as the local conditions and challenges that influence the sustainability of storm- and rainwater recycling. Particularly, this study aimed to show how well existing storm- and rainwater recycling systems have performed, relative to the level of ambition held by the project owner and try to gauge the systems' sustainability relative to traditional drinking water production systems, to see whether or not they could substitute drinking water where potable water is not needed. To achieve this, a literature study, a series of interviews with project owners and a multi-criteria analysis were conducted.

The evaluated storm- and rainwater recycling systems performed well at both larger and smaller scales, although this was not uniform. Generally, more simple systems with minimal treatment performed better. The relative lack of experience with the systems, regulatory uncertainties as well as the cold climate were all challenges that the storm- and rainwater recycling systems faced.

Broadly, the owners of the systems reported high levels of contentment with the systems and the quality of the water, but motivations for installing the systems varied between regions. Difficulties encountered generally pertained to issues that arose from the design, such as the storage being underdimensioned, or the turbidity of the water in open storage being too high, complicating treatment.

There appears to be potential for applying storm- and rainwater recycling at scale in Scandinavia. In theory, such technologies deployed at scale could help ease the demand for drinking water in all Scandinavian nations. Overall, storm- and rainwater recycling may not be a panacea for the water-related challenges brought on by climate change and industrial activity, but they can be part of a solution and alleviate some issues like water shortages.

Key words: Storm- and rainwater recycling, rainwater harvesting, reuse of rainwater, alternative water supply, Scandinavian climate, roof-runoff.

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Referat

Detta examensarbete undersökte det aktuella tillståndet av dag- och regnvattenåtervinning för användningsområden där drickbart vatten inte behövs i Skandinavien, exempelvis toalettspolning, samt de lokala förhållanden och utmaningar som påverkar hållbarheten av dag- och regnvattenåtervinning. Studien fokuserade särskilt på hur existerande dag- och regnvattensystem har presterat, relativt till den ambitionsnivå som fanns hos systemägarna, samt att försöka att utvärdera hållbarheten av dessa relativt den traditionella skandinaviska dricksvattenproduktionen. För att åstadkomma detta så genomfördes en litteraturstudie, flertalet intervjuer samt en multikriterieanalys.

De utvärderade dag- och regnvattenåtervinningssystemen presterade väl på både stor och liten skala, men samtliga gjorde inte det. Generellt så var det de enklare systemen med minimal behandling som presterade bättre. Den relativa bristen på erfarenhet med dessa system, osäkerheter angående lagar och förordningar, samt det kalla klimatet var utmaningar som mötte dag- och regnvattenåtervinningssystemen.

Generellt så rapporterade ägarna av systemen en hög nivå av tillfredsställelse med hur systemen har fungerat i praktiken samt kvaliteten på vattnet, dock så varierade motiveringarna bakom installationerna mellan olika regioner. Svårigheter som uppstod berodde ofta på problem som uppkom från designen av systemet, exempelvis underdimensionering av lagringskapacitet eller för hög grumlighet i vattnet som försvårade behandling.

Det verkar finnas potential för att använda dag- och regnvattenåtervinning på stor skala i Skandinavien, och storskalig applikation av dag- och regnvattenåtervinning skulle kunna bidra till att minska dricksvattenanvändningen i samtliga skandinaviska länder. Överlag så är kanske inte dag- och regnvattenåtervinnig en mirakellösning till vattenrelaterade utmaningar orsakat av klimatförändringar och industriell aktivitet. Dock så kan dag- och regnvattenåtervinning ändå vara en del av lösningen och lindra problem så som vattenbrist.

Nyckelord: Dagvatten, regnvatten, recirkulering, vattenåtervinning, Skandinaviskt klimat, regnvatten från tak.

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Foreword

This master’s thesis concludes five years of study at both Uppsala University and the Swedish University of Agricultural Sciences in the spring of 2024, and was conducted on behalf of Tyréns Sverige AB. The supervisors at Tyréns have been Johan Kjellin and Johan Åström, subject examiner Verena Germann at the institution of energy and technology at SLU, and examinator Antonio Segalini.

I would like to thank both of my supervisors, as well as Laila Søberg and Julia Granlund at Tyréns, for their support and assistance during the project. Likewise, I also extend my thanks to both Verena Germann and Jennifer Mcconville at the institution of energy and technology at SLU who helped to formulate the scope of the method and provided very helpful feedback.

The participation of the interviewees within the water sector and stakeholders in storm- and rainwater recycling systems was essential, and I am grateful for each one that took time out of their day to be part of this study.

Lastly, I would also like to thank my partner Tilda, for her constant support and help in acting as a sounding board throughout the process.

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Populärvetenskaplig sammanfattning

I dagsläget så används dricksvatten av livsmedelskvalitet till många användningsområden, likt toalettspolning och tvätt, där vatten av sådan kvalitet egentligen inte skulle behövas. I kombination med att samhällens vattenförsörjning hotas av överanvändning och klimatförändringar så lyfts alltmer ofta återvinning av regn och dagvatten, exempelvis smältvatten eller vatten som rinner av vägar, upp som en möjlig lösning på att säkra vattenförsörjningen.

Idén bakom är att i stället för att låta dag- and regnvattnet rinna ut via brunnar och ledas bort, så kan det i stället användas till saker just som toalettspolning, och på så vis kan dricksvattenresurser sparas. Det finns redan återvinningssystem av dag- och regnvatten i större skala globalt, men det är hittills ganska sällsynt i Skandinavien.

Detta examensarbete gick ut på att utvärdera om återvinning av dag- och regnvatten är något som skulle vara hållbart i Skandinavien, med avseende på den rikliga tillgång på billigt dricksvatten som finns i Sverige, Norge och Danmark. För att göra detta genomfördes en litteraturstudie, ett flertal intervjuer med ägare av återvinningssystem och en multikriterieanalys där exempelvis energikonsumtion och kostnader utvärderades.

Litteraturstudien visade att, i alla fall teoretiskt, dag- och regnvattenåtervinning kan bidra till att motverka flera problem, så som vattenbrist, översvämningar och överbelastning på vattenrörledningar. Där för mycket vatten på samma gång kan leda till att brunnar helt enkelt inte hinner med och vattnet i stället hamnar där det inte ska, likt i källare.

Enligt litteraturstudien så skulle dag- och regnvattenåtervinning ha möjligheten att bidra med flera procent av de skandinaviska ländernas totala vattenförbrukning, bara genom att ersätta dricksvatten för toalettspolning och tvätt av kläder med återvunnet vatten. Detta skulle bidra till att säkra dricksvattenförsörjning till där dricksvatten faktiskt behövs om vattenbrist uppstod. Därtill finns det även potential för utökad användning av dag- och regnvatten till exempelvis industriell produktion och bevattning.

I intervjuerna så deltog ägare av olika dag- och regnvattenåtervinningssystem från Sverige, Norge och Danmark, där de frågades om erfarenheterna de har haft med sina system. De som intervjuades var generellt nöjda med sina system och tyckte att vattenkvaliteten var god. Dock så hade flera insett att det var viktigt att systemen designades på ett bra sätt från första början, exempelvis genom att det fanns tillräcklig god lagringsförmåga för det återvunna vattnet.

Några utmaningar som systemägarna mötte var otydliga lagar, osäkerhet angående vilka som skulle bära kostnad för det ersatta dricksvattnet hos kommuner och, för de som fanns längre norrut så var även snö ett problem. Likaså kunde det uppstå svårigheter att kommunicera hur systemen fungerade i praktiken till utomstående.

I multikriterieanalysen så ställdes energianvändning, koldioxidutsläpp, investerings- och driftkostnader samt tillgänglighet av systemen mot ett teoretiskt återvinningssystem som utnyttjade dricksvatten, för att se hur hållbara dag- och regnvattenåtervinningssystemen var i praktiken gentemot det dricksvatten som finns i Skandinavien.

Det visade sig att på det stora hela så kan dag- och regnvattensåtervinning vara ett bra alternativ till dricksvatten, dock var det inte alltid det bästa alternativet enligt analysen, men kunde bevisligen vara mer hållbart inom ramen för de parametrar som utvärderades. Om dricksvatten är det bättre alternativet över återvunnet dag- och regnvatten eller inte beror på designen och hur avancerat dag- och regnvattensystemet är. De enklare och mindre komplicerade återvinningssystemen som använde regnvatten insamlat från tak, och med begränsad behandling, var generellt de som var mest hållbara.

Sammantaget så påvisade detta examensarbete att dag- och regnvattenåtervinning kan vara ett hållbart alternativ till traditionell dricksvattenproduktion även under skandinaviska förhållanden, där det länge funnits goda tillgångar på billigt dricksvatten. Även att det finns potential för sådan återvinning att agera som ett komplement till den dricksvattenförsörjning som redan finns.

Glossary

ARI - Average Recurrence Interval, a term to describe the average recurrence interval of rainfall of a certain intensity.

Artificial infiltration - The pumping of stormwater into soil to replenish groundwater reserves.

Criteria – Used in this study to denote various aspects, particularly concerning sustainability, that are considered when evaluating a system. Criteria includes environmental, economic and technological factors, and the parameters used in the multi-criteria analysis were derived from the criteria.

Non-potable water – Water not at the quality of drinking water and unfit for human direct consumption.

Parameters - Used in this study to denote the five parameters used to evaluate the systems in the multi-criteria analysis, such as energy intensity.

Potable water - Water at the quality of drinking water and suitable for human direct consumption, used synonymously with drinking water.

Rainwater - A part of stormwater, although specifically referring to water from rainfall directly, rainwater only brings with it the contaminants from the very specific surface it falls upon and as such is generally cleaner than other forms of stormwater.

Rainwater harvesting - The collection of rainwater intended for using it, used synonymously with rainwater recycling.

Scope 1, 2 and 3 emissions – Scope 1 emissions covers those from sources owned/operated by the emitter directly, Scope 2 includes emissions from the production of the energy used. Scope 3 includes indirect emissions up and down the value chain (National Grid Group 2024).

Storm- and rainwater recycling - An umbrella term for various methods of collecting storm- and rainwater and reusing it for purposes such as flushing or irrigation.

Stormwater - An umbrella term for rainwater, meltwater, urban run-off and other temporary water flows that do not percolate into the ground.

Traditional drinking water systems - An umbrella term that refers to the municipal utility-owned and operated collection, treatment, storage and distribution of drinking water to customers, excluding wastewater or stormwater.

Traditional water systems - An umbrella term that encompasses the municipal utility-owned and operated collection, treatment, storage, distribution and sewage networks as well as infrastructure.

Wastewater - An umbrella term for water that is discarded or diverted as waste, often after human use, such as sewage, industrial process water and greywater from households.

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1. Introduction

1.1 Introduction to storm- and rainwater recycling

In a world with increasing water insecurity and extreme weather brought on by climate change and human consumption, the sustainable use of water has become more urgent in later years (IPCC 2022). Longer periods of drought, interspersed by heavy rainfall and increase in urban sprawl with artificial and less permeable surfaces, adversely affects infiltration necessary to replenish aquifers (National Weather Surface n.d.). In turn, decreased infiltration together with demands on aquifers arising from industrial processes has contributed to water shortages and unsustainable pressure on groundwater in many places. Amongst the Scandinavian countries it is Denmark, largely relying on groundwater for their water needs, that is more adversely impacted, but local and regional water shortages are also prevalent elsewhere in Scandinavia (International Water Association 2022).

Globally it is increasingly common for storm- and rainwater to be viewed as a resource, and not merely as waste or an issue that must be contemplated in urban planning. The collection and recycling of storm- and rainwater can contribute to mitigating several challenges facing societies, such as water scarcity, flooding and strain on traditional drainage systems (Mitchell et al. 2006). It is already a well-established practice in more arid regions such as Australia, however the recycling of storm- and rainwater is still a nascent industry in Scandinavia (Campisano et al. 2017). As such, how well-suited it is to Scandinavian conditions is still unclear when compared with traditional water systems.

Traditionally, stormwater is diverted into lakes and waterways directly, with the exception of where the sewage system uses combined pipes where sewage as well as stormwater is transported jointly to water treatment plants, or when it is polluted and treated at a stormwater treatment facility. When diverted in combined pipes it is only released into natural bodies of water after being treated as wastewater (South Australian Environmental Protection Agency 2021; Swedish Environmental Protection Agency 2024a). Despite surface water, like lakes and rivers, being heavily utilised in countries like Sweden, both for the production of drinking water and to replenish groundwater through artificial infiltration (Svenskt Vatten 2016), there is not much utilisation of storm- or rainwater anywhere in Scandinavia (Svenskt Vatten 2016; Norsk Vann 2024; International Water Association 2022). The use of rainwater directly is rare, despite the relatively high quality of it when it is collected on a clean surface.

In theory when only considering the quantity of drinking water that could be substituted, storm- and rainwater has considerable potential for expanded use, to complement traditional water supply and help shore up water security in dry periods (Mikkelsen 1999). It is therefore important to understand how storm- and rainwater recycling systems perform under Scandinavian conditions and what challenges storm- and rainwater recycling systems face, something that this study sets out to bring more clarity to. Whether or not it is a viable source of sustainable alternative water, or merely something that sounds sustainable but in practice is not.

This report was conducted on behalf of Tyréns Sverige AB to complement the wider research project, Drizzle, to evaluate a number of storm- and rainwater recycling projects that have already been established in Scandinavia.

1.2 Tyréns Sverige AB

Tyréns Sverige AB is a multinational consultant firm with approximately 3000 employees. It is mainly based in Sweden, but also active in England, Estonia, Lithuania, Poland and Bulgaria. The firm primarily works with sustainable urban planning and infrastructure, and is owned by a foundation. On Tyréns' website, the company states that being foundation-owned enables a greater emphasis on research and development (Tyréns n.d.)

1.3 Drizzle

Drizzle is a research project initiated by Luleå University of Technology and partially funded by Vinnova, the Swedish innovation authority. It is conducted by a number of actors including Tyréns as well as other companies, but also other actors such as water utility companies and municipalities. Tyréns within the project have a particular emphasis on the recycling of storm- and rainwater, although the project as a whole covers stormwater more broadly. The stated purpose behind Drizzle is to create innovative stormwater solutions that mitigate risks of flooding, reduce pollutant loads on lakes and waterways as well as utilise the possibilities that stormwater runoff offers (Tyréns 2018).

1.4 Objective of the thesis

The overall purpose of this study is to evaluate how sustainable storm- and rainwater recycling solutions are for activities not requiring water at the quality of drinking water: In regard to the climate and other local conditions, when compared with the ready access and cheap cost of potable water found in Sweden, Denmark and Norway. As the region has traditionally enjoyed abundant freshwater resources, this study attempted to uncover if storm- and rainwater as a concept would be sustainable compared to traditional drinking water, or if it was merely something that sounded sustainable, but in reality was not.

The study also sought to uncover that if it indeed could be a sustainable source of alternative water, then also find out what technological solutions are most sustainable in practice. That is, what the systems that performed best had in common, whether or not there were any particular traits that they shared that contributed to them being more sustainable.

Another objective of the study was to gather important insights into experiences of those that have installed storm- and rainwater recycling systems, as to help others that may be interested in installing them avoid certain pitfalls, and provide insight into how storm- and rainwater recycling systems operate. Relevant to this was to find out whether or not the systems in operation had lived up to the level of ambition that the stakeholders originally had.

1.5 Research questions

Related to the objectives outlined above, the following research questions were considered:

- Can storm- and rainwater recycling practices for non-potable water be sustainable in Scandinavia, relative to climate and other local conditions, when compared to traditional drinking water?
- In practice, what system configurations of storm- and rainwater recycling have proven themselves to be sustainable for stormwater recycling for non-potable water in Scandinavia?
- Have existing storm- and rainwater recycling projects for non-potable water in Scandinavia reached the level of ambition set out during their planning phase, and as such functioned as the stakeholders intended?

1.6 Delimitations & Scope

The study seeks to provide an overview of storm- and rainwater recycling systems in Scandinavia - From how they operate, to how they have performed relative to traditional drinking water systems, and to put this performance into a context of the local challenges they face. Based on both literature and experience from the local stakeholders, the aim is to provide a comprehensive overview of existing storm- and rainwater recycling technologies and how they function in Scandinavian conditions.

Chiefly, the study aims to provide a two-fold evaluation as to how storm- and rainwater recycling projects have performed in practice. This evaluation in turn consists of quantitative, as well as qualitative factors. The quantitative factors consist of parameters such as energy consumption and operating costs, with the qualitative factors covering aspects such as satisfaction with and perceived quality of the system by the stakeholders.

Another important part of the study was to explore the conditions that apply to these systems in Scandinavian countries. This included the local meteorological and regulatory climate, as well as their traditional systems and potential ambitions for recycling of water. For the sake of brevity and to maintain the focus, the study attempts to give an overview on matters such as the local law, national guidelines and stated ambitions, rather than an in-depth legal or political analysis.

Due to time constraints the study did not include social criteria in the multi-criteria analysis, such as user satisfaction and microbial health hazards, in the multi-criteria analysis. The choice to exclude the social aspect from the multi-criteria analysis as such does not reflect an opinion that social criteria in general are less important than the criteria in the present study. Furthermore, as the various projects evaluated in this study do not include water intended directly or indirectly for human consumption, as the emphasis on water quality is not stringent as it otherwise would have been. Particularly as rainwater in and of itself is not inherently polluted.

The evaluated storm- and rainwater recycling systems included some 15 systems preselected by Tyréns that they had found when searching for storm- and rainwater recycling systems. Of these 15, 7 are located in Denmark, 5 in Sweden and 3 in Norway. The systems that were approached for interviews, some thirteen in total, were selected on the criteria that there were at least two systems selected from in each country, and that there were other systems using water for similar purposes such that they could be compared. The three most common end-uses, and those whose end-use could be found in at least one other location, were water closets (WC) flushing, washing machines and irrigation.

2. Background

2.1 Storm- and rainwater

Stormwater is a term used to describe different forms of temporary water flows, including rainwater, floodwater, meltwater and emergent water rising from the soil (Nationalencyklopedin 2023). Although rainwater is a component of stormwater, it is as such not used interchangeably with stormwater in this study, given that stormwater has greater risks of carrying more pollutants and particles when it runs off hard surfaces. With rainwater only carrying that which it comes into contact with immediately upon the surface it falls (South Australian Environmental Protection Agency 2021).

Commonly, stormwater runs off hard surfaces and soil with insufficient permeability, such as those already saturated with water or not porous enough. This necessitates drainage systems to divert the water, particularly in areas with urban sprawl where more artificial hard surfaces akin to roofs and asphalt are prominent. Unable to penetrate these to infiltrate into soil, the water must be diverted to avoid flooding, which is normally done by using drainage systems to allow the water to drain into streams and other natural water bodies (South Australian Environmental Protection Agency 2021).

Stormwater differs from wastewater in that it has not been subjected to human use, e.g. flushing or in industrial processes, therefore it is not generally treated in wastewater treatment plants (NSVA n.d.). That does not mean that stormwater is devoid of pollutants. Contrary, stormwater is a significant carrier of pollutants such as oil, metals and rubber as it sweeps them with it when running off hardened surfaces like roads and rooftops (South Australian Environmental Protection Agency 2021).

Heavy metals, nutrients, pathogens, oil, preservatives and waste are just a few examples of what the stormwater can bring with it. A summary of contaminants can be found in Table 1. The quality of stormwater is as such dependent on the cleanliness of the surfaces along which it travels before it reaches its final destination, either for use or drainage into a natural water body (South Australian Environmental Protection Agency 2021).

Table 1. Examples of pollutants in stormwater and the corresponding effects on health and environment (Mitchell et al. 2006)

Examples of pollutants found in stormwater	Examples of effects on health and environment
Gross pollutants and litter	Harmful and non-degradable materials introduced to aquatic ecosystems, loss of recreation etc.
Sediment and suspended solids	Less penetration of sunlight, potentially smothering ecosystems.

Nutrients (phosphorus and nitrogen)	Potentially toxic algae blooms resulting in oxygen depletion and less sunlight penetration.
BOD/COD (degradable organic matter)	The depletion of oxygen through microbial activity, resulting in the smothering of aquatic ecosystems.
Microorganisms	Spread of pathogens and water-borne diseases, posing risks to human health.
Toxic organics and trace metals	Toxic effects on ecosystems, such as the precipitation of metals on gills, and bioaccumulation of pollutants in organisms.
Oils and surfactants	Toxic effects on aquatic ecosystems. Can form films on surfaces of the water and decrease sunlight penetration, smothering ecosystems.

2.2 Traditional drinking water systems

Traditional drinking water systems can vary in scope and centralization, but commonly consist of collection from some source of water (ground- or surface water) followed by water treatment and distribution. Some systems are highly centralised, providing potable water to entire cities, with massive water treatment facilities (Paraschiv et al. 2022). In Sweden, Denmark and Norway, the water utility companies are chiefly owned by the municipalities and are not intended to make profits, meaning that a desire for profit margins as a means of appeasing shareholders is not a factor in the pricing of drinking water (Svenskt Vatten 2023; DANVA 2022; Norsk Vann 2024).

The cost and energy consumption of drinking water production depends on a number of factors, such as the quality of the water used for the production. For instance, seawater requires desalination due to high salt content. Desalination is a costly process making seawater considerably more expensive water resource than groundwater. Other factors influencing cost include the power supply, choice of treatment technologies, local energy costs, quality requirements and future distribution expansion needs.

On average, a study conducted in 2022 found that in the US and China, the energy consumption for the production of drinking water was 0.34 kWh/m^3 and 0.29 kWh/m^3 respectively (Paraschiv et al. 2022). In comparison, as per the European Environment Agency (2024), the consumption of energy for drinking water production and distribution is 0.93 kWh/m^3 as a weighted mean for Sweden and 0.44 kWh/m^3 as a weighted mean for Denmark. Though they range between 0.41 - 1.38 kWh/m^3 for Sweden and 0.37 - 0.69 kWh/m^3 for Denmark. Data for Norway was not present.

In a report from Sydvatten (2022), a water utility company in southern Sweden that supplies water to one million people, carbon intensity per cubic metre of sold tapwater for themselves and a number of water utility companies were covered. These were chiefly from the Netherlands but also included one from Spain and another two from Poland. Evident in the report is a significant discrepancy in carbon intensity between different countries, arising partially from differing power supply sources and treatment techniques. Renewable power sources were counted as not contributing carbon emissions (Ibid.).

Since this study only focuses on the energy consumption on site, Scope 3 emissions that include transports, production of chemicals and trips relating to the operations will not be measured against the recycled water systems. That which was taken into account was the Scope 1 and Scope 2 emissions for Sydvatten, including the machinery, spare power and other consumption directly at their facilities, as well as external electricity bought to supply the process, were 2 gCO_2/m^3. With Sydvatten stating that they exclusively purchase renewable energy to supply their facilities, including the treatment of drinking water and its distribution, contributing to the low carbon intensity. The average when including other European water utility companies was considerably higher at 165 gCO_2/m^3. The carbon intensity for drinking water produced by Sydvatten, when calculated by the regional average carbon intensity of the power grid in 2023 (41 gCO_2/kWh), instead yields 13 gCO_2/m^3 (Electricity Maps 2024).

According to Svenskt Vatten (2023), Swedish drinking water for a single-family home costs about 61 SEK per cubic metre (5.4 EUR/m^3) on average although varying between 112 SEK/m^3 and 23 SEK/m^3 depending on the municipality. For a typical apartment, the costs are slightly lower at 43 SEK on average per cubic metre (3.8 EUR/m^3). This includes taxes and costs for the treatment of wastewater. The customers finance the water utility companies through taxes and the services they buy, with the fees covering everything from the production and distribution of drinking water to the treatment of wastewater (VIVAB 2023).

The cost of Danish tapwater is significantly higher, at 9.85 EUR/m^3 on average for households, although only a third of that cost directly covers the production of drinking water (at 3.28 EUR/m^3) as per DANVA (2022), with the majority pertaining to wastewater costs and taxes. In Denmark, the water utility companies and their services are fully covered by the fees paid by customers. In Norway, as per the head of the department for water services at Norsk Vann, Kjetil Furuberg[1], the price of Norwegian tapwater was on average 52 NOK/m^3 (4.5 EUR/m^3) as of 2023. Although this number could differ depending on the building and number of users. Costs are presented in Figure 1.

[1] Kjetil Furuberg, Head of Department of Water Services at Norsk Vann, Mail, 2024-03-01

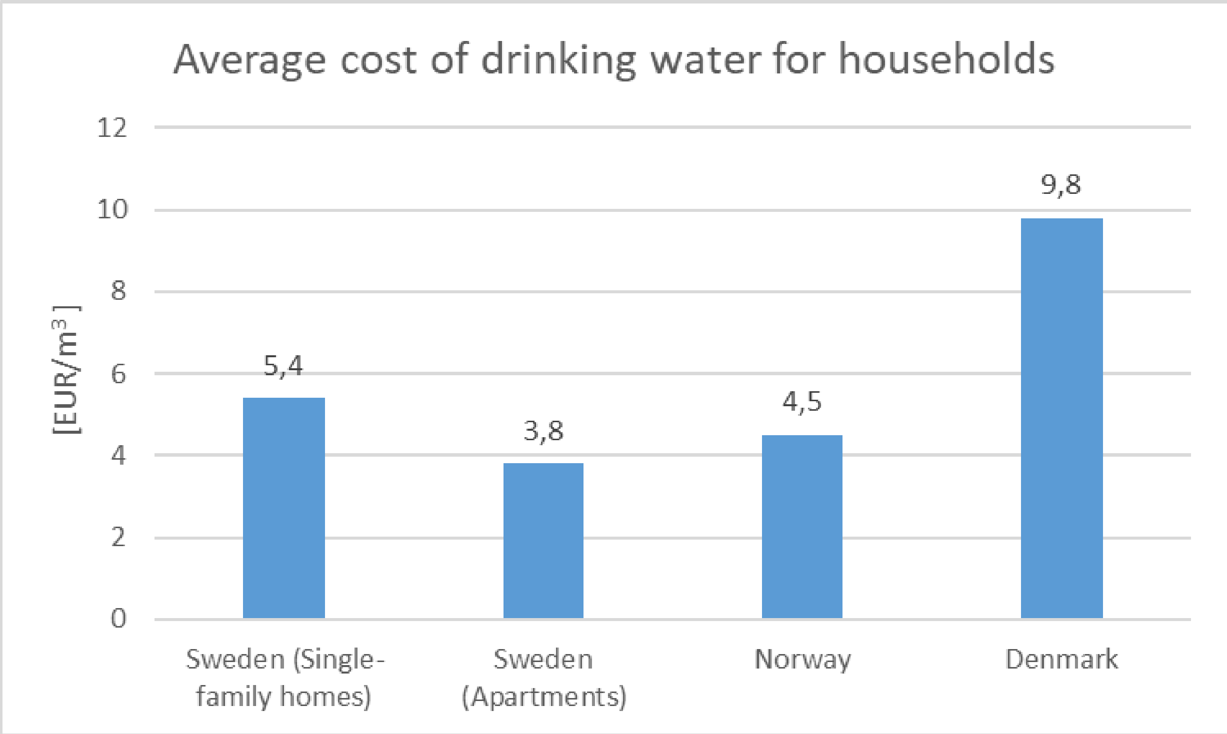

Figure 1. The average cost of drinking water for households in Sweden, Norway and Denmark (Svenskt Vatten 2023; DANVA 2022; Norsk Vann 2024)

2.2.1 Investment costs of traditional drinking water production

According to Svenskt Vatten (2023b), the investment cost of a drinking water production plant varied between 5000-10000 SEK/PE as of 2021, or equivalent to roughly 528-1044 EUR/PE converted to Euro and adjusted for inflation.

With an estimated technical lifespan of 50-100 years [2] of a plant, and 140 litres per person and day counted as a population equivalent (PE) (Svenskt Vatten 2021), the investment cost per cubic metre over the plant's lifespan is 0.10-0.41 EUR/m^3.

Furthermore, Svenskt Vatten (2023b) estimates the investment cost for replacement or expansion of the distribution network as of 2021 to be approximately 7000 SEK per metre. The same report also gives a number of some 6.1-62.5 metres of distribution network per person in place today, with the low end being in large cities, and the high end being in sparsely populated areas. This in turn equals an investment cost of 42700-437500 SEK/PE, or 4460-45680 EUR/PE when converted to Euro and adjusted for inflation.
Considering the average water consumption per person and an assumed lifespan of the pipes of 100 years [3] as well as the fraction of the distribution network that is for drinking water, as to exclude drainage and other segments of the distribution network not strictly to distribute drinking water, this results in an investment cost of 0.37-3.75 EUR/m^3.

[2] Mats Engdahl, Expert of Drinking Water Production at Svenskt Vatten, Mail, 2024-04-15
[3] Mats Engdahl, Expert of Drinking Water Production at Svenskt Vatten, Mail, 2024-04-15

An approximation of the investment cost per cubic metre over intended lifespan for traditional drinking water systems, with both drinking water production and distribution included, is as such roughly around 0.47 - 4.16 EUR/m^3.

2.2.2 Risks to traditional water systems from global instability

An additional case for both the securing of additional supply of water for non-potable purposes, and as such decreasing the demand for drinking water, arose from the disruption of global supply chains as a result of various crises between 2020-2023. A pandemic, intensified armed conflicts, economic downturn, high energy costs and regional instability have contributed to difficulties with supply. To maintain function, drinking- and wastewater systems are dependent on a number of chemicals and other inputs. In an assessment made by the US Environmental Protection Agency in 2023, some forty-six chemicals directly used or indirectly used as inputs for the production of direct-use chemicals in treatment processes globally could be at risk. This means that traditional water treatment systems are vulnerable to disruption, and as a consequence, the water supply for residents in the affected nations (US Environmental Protection Agency 2023).

2.3 Recycling of storm- and rainwater

2.3.1 Motivations for storm- and rainwater recycling

Despite potential quality hazards, storm- and rainwater has the potential to act as a valuable resource and alternative water supply. Rainwater is not as polluted as other types of stormwater and only carries pollutants from the specific surface upon which it falls (South Australian Environmental Protection Agency 2021).

If collected with caution to ensure the quality of the water is fit for whatever purpose is desired, the use of storm- and rainwater can have several benefits, as outlined in Figure 2. Chiefly among them is that it helps to secure additional freshwater supply, which in turn can help boost water security and alleviate issues like drought, but also reduce demand on traditional water systems (Hatt et al., 2006). Through the use of storm- and rainwater to replace potable water used for non-potable purposes, the strain on potable sources of water such as groundwater is reduced. This has become increasingly important owing to how freshwater use has outstripped population growth, with the use of freshwater rising sixfold even as the population rose just twofold between 1900-1995. However, there had been little focus on storm- and rainwater recycling on a larger scale in international literature, nor had any comprehensive review as to effectiveness been conducted as of 2006 (Hatt et al., 2006).

Securing alternative sources of water will be of increasing importance based on the projections of the Intergovernmental Panel on Climate Change (2022). The IPCC (2022) states that the effects of climate change have been observed to cause shifts in global precipitation patterns, with increased water insecurity, more extreme weather and adverse effects caused by flooding.

Another issue associated with climate change and an increasing number of extreme precipitation events as well as longer periods without precipitation, is how it creates conditions suboptimal for the infiltration of water into the soil and as such the replenishment of groundwater aquifers (National Weather Service n.d.). Collected storm- and rainwater can as such replace some drinking water where the water is not needed at potable quality and reduce risks of exhausting vulnerable aquifers.

Beyond water security, another benefit to storm- and rainwater recycling is that it can control flows and to some extent even decrease local flooding (Hatt et al. 2006). With cities expanding due to centralization and a growing population, existing infrastructure becomes insufficient to handle precipitation and in particular extreme precipitation events (IPCC 2022). In its fourth report of 2022 the Intergovernmental Panel on Climate Change stated that between the years of 1970 and 2019, roughly a third of global economic losses were attributed to flooding (ibid.). Effective reuse strategies of stormwater can decrease the need for drainage infrastructure, and potentially costly treatment of polluted stormwater (South Australian Environmental Protection Agency 2021).

As per the US Environmental Protection Agency (2023), stormwater is the single largest cause of nonpoint source pollution, meaning pollution not having a clearly defined source. As previously mentioned, stormwater moves over and through the ground, bringing with it various pollutants it comes across. Decreasing runoff by making effective use of stormwater, through harvesting and recycling it instead of allowing it to flood over a wider area, could in theory improve overall environmental health of waterways and other recipients.

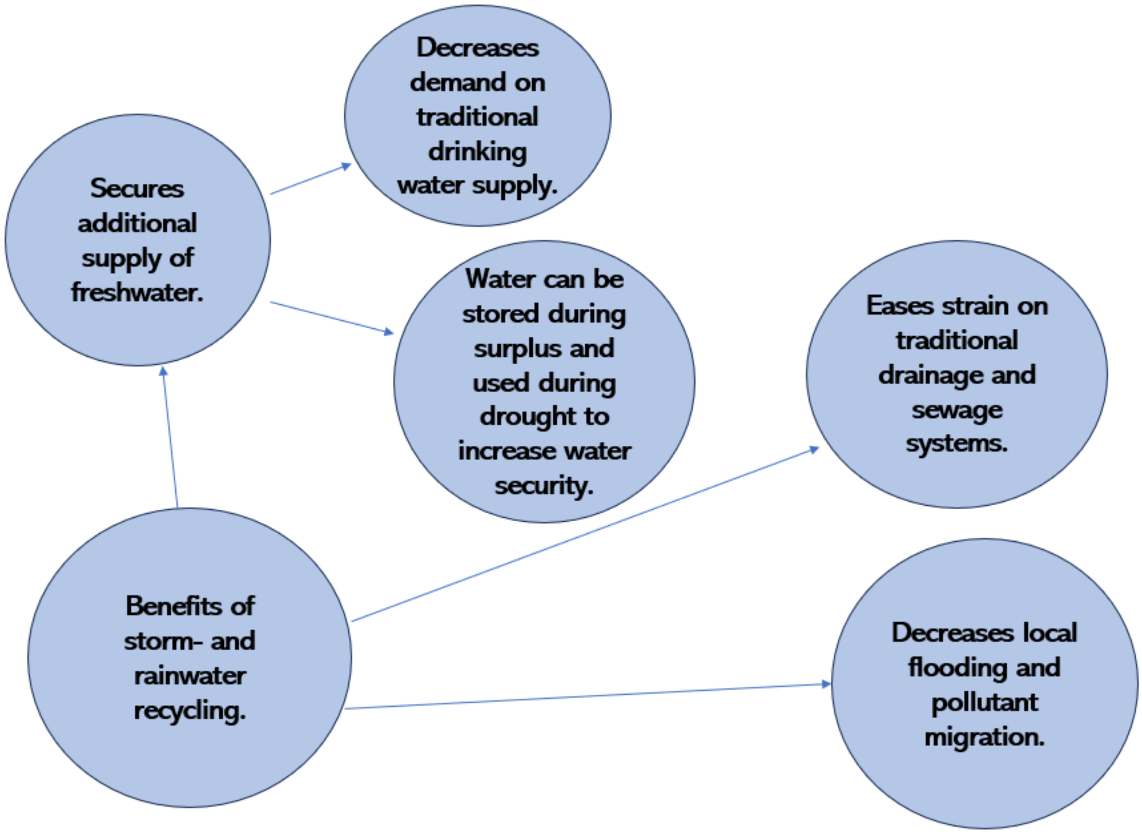

Figure 2: Chart of potential benefits of storm- and rainwater recycling

2.3.2 Storm- and rainwater recycling globally

As previously mentioned, though storm- and rainwater recycling is not widespread everywhere, there is already a significant deployment of storm- and rainwater recycling systems globally. The reasons can however vary. For instance, at many places in Africa storm- and rainwater recycling is not always due to physical water scarcity, rather due to a lack of economic resources to collect, treat and distribute it in more centralised systems. Therefore, it can be an economic boon to collect relatively clean rainwater, and small-scale installations are common (Campisano et al. 2017).

In Asia, successive governments in Japan, Thailand as well as the authorities in China have promoted rainwater harvesting solutions. Despite storm- and rainwater recycling covering just a fraction of the total water consumption, the cumulative effect of numerous small-scale stormwater recycling systems has resulted in significant quantities of recycled water, providing water equivalent to the consumption of millions of people throughout Asia. Such as 2 million in the Chinese province of Gansu alone by the year 2000, with the number of storm- and rainwater recycling systems increasing drastically there since. In Taiwan, it is mandated to have a storm- and rainwater recycling system that provides at least 5% of the total water consumption for all buildings larger than a hectare (ibid.).

In Australia, the implementation of storm- and rainwater recycling systems is common, owing to Australia's climate and warm temperatures. As per a survey in 2015, 1.7 million households in Australia had at that time fitted rainwater harvesting systems, constituting a capacity equal to 8% of the total household water use in Australia. The most common end-use being various in-building applications, such as for flushing or washing (ibid.).

Common uses of recycled stormwater in Australia according to Hatt et al. (2006) included irrigation of gardens and public outdoor areas, toilet flushing, washing of cars and windows, recycling for environmental flows and firefighting. A collection of other uses outlined in the report included various industrial uses (ibid.).

A study conducted in Australia with more than 1200 participants found that acceptance in regard to using rainwater and treated stormwater both were rather broad, with respondents answering to being least comfortable with recycled water for human consumption. But even amongst these, acceptance for recycled water was higher than for nuclear energy and genetically modified food (Fielding et al. 2015).

In the United States, there are significant discrepancies between states, with more deployment of stormwater recycling systems in states like Texas. Financial incentives are offered to homeowners wishing to install them, as a water-conserving measure. It is allowed in other states, such as Oregon and New Mexico, but there are stringent regulations as to the use and quality of the recycled water. Meanwhile, in South America, there have been large-scale projects in more arid regions to create systems of rainwater harvesting, as a bid to secure an alternative water supply (Campisano et al. 2017).

In Europe, there are significant discrepancies between different regions as to the prevalence of stormwater recycling systems. In some countries, like the UK, use of rainwater for household use is traditionally widespread (ibid.). Several nations in western Europe have also begun to introduce systems of stormwater recycling in a bid to conserve and reduce the strain on the municipal supply of drinking water and groundwater resources (ibid.). Financial viability for smaller systems is part of the reason why smaller-scale systems in the UK are still less numerous than larger, more commercial systems, such as those installed in public buildings. With smaller systems being slower to recoup the initial investment from savings in water (Melville-Shreeve 2016).

Germany is a leader in Europe regarding the recycling of stormwater, with approximately 1.8 million households and companies recycling water through the harvesting of rainwater as of 2009. A large portion of newly constructed buildings are constructed with rainwater harvesting systems, owing to various subsidies and grants providing economic incentives to install them (Ziegler 2017). Besides the smaller-scale systems for households, Germany has examples of large storm- and rainwater recycling systems such as that at Frankfurt Airport, capable of recycling a million cubic metres a year. Due to considerable air pollution from industrial activity, and strict regulations concerning drinking water standards, the recycling systems of storm- and rainwater in Germany can only recycle water for non-potable uses. Mainly flushing, irrigation and laundry (Rainwater Harvesting n.d.).

Other nations where storm- and rainwater recycling systems can be found and are increasing in number, include Spain, Italy and Austria. Broadly, there has been increasing interest toward recycling of storm- and rainwater, with economic incentives and technical guidelines issued in these countries (Campisano 2017).

2.3.2.1 Costs and performance of storm- and rainwater recycling systems in literature

Investment and operating costs of storm- and rainwater recycling systems in literature:

How much a storm- and rainwater recycling system costs can vary dramatically depending on factors such as the scale of the system, and the spatial size it covers. In a survey conducted by the Minnesota Pollution Control Agency back in 2016, 26 different systems were included, and their total investment costs were presented. Out of the 26 in total, some 22 were irrigation systems that ranged in total costs between 1500-1500000 USD. Toilet flushing systems, some of them incorporating car washing besides flushing, ranged between 57500-300000 USD in total costs (Minnesota Pollution Control Agency 2024). Adjusted for inflation and converted to EUR, these investment costs are roughly equivalent to 1800-1800000 EUR.

Major components that can contribute to the overall cost include land acquisition, excavation and removal of materiel, as well as storage and treatment (ibid.). Due to high investment costs, the Minnesota Pollution Control Agency (2024) states that it is often necessary for stakeholders to rely on more than one source of funding, such as loans and grants from the state, or other forms of public or private financing. Out of the 26 systems, 16 had needed to use two or more sources of funding.

While the investment costs can be substantial, operating costs are generally lower, albeit depending on factors such as how advanced the treatment is. As per GRAF UK Ltd, a supplier of water management systems, the low operating costs can result in a return on the initial investment over time. For a simple and small-scale system not requiring maintenance, a storm- and rainwater recycling system can have as low operating costs as 2-6 EUR per year. For these, energy intensity can range up to 1.5-2 kWh/m^3 (GRAF 2024).

Such minimal costs are not necessarily the norm, however, especially not for systems requiring some degree of maintenance or using more advanced treatment. Examples of more expensive systems can be found in a study from 2020 by Fredenham et al., where the cost benefits for a number of rainwater harvesting systems in the UK was evaluated. The study grouped all systems with similar collection area and water production together and calculated average capital expenditure and operating costs for each category. Operating costs on average ranged between 650-3000 EUR, when adjusted for inflation and converted from British pounds, with investment costs for installing a rainwater recycling system generally ranging between 14000-84000 EUR. These systems varied in scale of collection area and water demand, with the largest dimensioned to produce more than 10000 cubic metres per year (ibid.).

Performance of storm- and rainwater recycling system relative to traditional drinking water systems in literature:

In regard to performance relative to drinking water, the previously mentioned and comprehensive study in the United Kingdom by Fredenham et al. (2020) conclude that rainwater recycling systems generally result in a net benefit for most buildings that had installed it. The potential benefits were greater for larger systems, particularly those with a high water demand. For the very largest, there was an added benefit of flood management. Smaller systems for buildings with low demand for water were however at higher risk for being a net cost to the stakeholder.

Performance more broadly was deemed to depend on a number of factors, e.g. how much water can be collected, the size of storage, maintenance costs depending on the scale and complexity of the system, as well as the energy consumption of the system. The annual rainfall at the site is a very important variable, and together with the size of the collection area, dictates the potential for how much water can be collected throughout the year (ibid.).

As per Fredenham et al. (2020), storm- and rainwater recycling systems have in past studies been suggested to emit more carbon and use more energy in its production than drinking water, but in more recent studies it has been shown that they can both use less energy and have lower emissions when viewed over their lifespan. As per the authors, this is due to recent innovations in pump design and low energy rainwater recycling systems. Fredenham et al. (2020) conclude that storm- and rainwater recycling systems can be more energy efficient and cheaper than drinking water, but that this depends on the system configuration and how the system is designed.

Storm- and rainwater recycling brings the greatest benefits as per Fredenham et al. (2020), when implemented strategically at larger scale. But as it is not always the better option relative to drinking water, each system should be considered individually and implemented on a case-by-case basis.

2.3.3 Storm- and rainwater recycling practices and techniques

There are a vast number of ways to construct a stormwater recycling system, however they generally consist of the same components. McMahon et al. (2008) describe five main components to the recycling of stormwater, explained in more detail in Table 2:

- End use
- Collection
- Treatment
- Storage
- Distribution

End use reflects the intended purpose for the water that is being harvested, where it is important to design the project based on what the water is meant to be used for and what specifications that requires. What is important is to ensure that the water quality is sufficient for the purpose and fulfils the quality enshrined in laws or recommendations, even if it does not necessarily have to exceed it. Water intended for potable use will necessitate that it is handled with more care than water intended for non-potable use (ibid.)

Collection corresponds to the component that gathers and stores the water intended for use. McMahon et al. (2008) remarks that the specific characteristics can vary greatly depending on the system and the nature of the storage, and that there is no uniform way of collecting stormwater. Some examples include the diversion of urban creeks, making use of stormwater drains, rooftop collection or general urban runoff.

Collection can occur through traditional systems or through water sensitive urban design (WSUD). The traditional systems of pipes, gutters and drainage can generally accommodate larger flows of at least two year average recurrence interval peak flows, although this can vary. WSUDs are constructed more specifically to harvest stormwater, and usually incorporate vegetated swale drains, filter drains or biofilters to ensure a higher water quality of that which is collected (Mitchell et al. 2006).

Solar panels are sometimes combined with the collection of rainwater, where studies have shown that solar panels can increase effectiveness of rainwater harvesting through temperature contrast between the surrounding air and the panels themselves, as well as the sloping surface. These factors contribute to greater condensation, and the glass surface of the solar panels improves the runoff coefficient (Alazzam et al. 2024).

Furthermore, Mitchell et al. (2006) elaborate on two different types of storage - online and offline. Online storage is fed water directly from the collection, whereas offline storage requires an additional collection system to divert water from an urban waterway once stormwater has already been collected, either by a traditional drainage system or a WSUD design.

A necessary step and the third component is treatment. The choice of treatment is influenced both by the characteristics of the catchment and collection, such as pollutants that can be swept along with the water. The other factor, as mentioned above, is the intended end use of the treated stormwater. These two together decide the necessary level of treatment, in accordance with water quality regulations and guidelines (Mitchell et al. 2006).

In practice, the treatment of stormwater adheres to principles of the treatment of water in general, in that it is done by a series of complementary steps and processes. Mitchell et al. (2006) discusses three different types of treatment steps suitable for the harvesting and reuse of stormwater. Some form of filtration such as with a biofilter, physico-chemical treatment depending on pollutants, and disinfection.

Biofilters are a term for filter material making use of biological processes for treatment, and this can involve both soil-based filters, ponds or other forms of landscaped areas. Stormwater is allowed to slowly move through the filter area. Vegetation and biofilms consisting of microorganisms contribute to uptake of pollutants, such as heavy metals, and nutrients. Organic compounds are broken down by biological degradation, whereas others are removed by way of mechanical filtration, sorption and other processes like sedimentation. The biological treatment is only effective however as long as the local environment is suitable for the microorganisms and vegetation whose biological processes are used to treat the water. It requires that the temperatures are kept at that which the microorganism can thrive in and that pollutants are kept at non-toxic concentrations, as it otherwise could result in the treatment being hampered or even halted due to microorganisms ceasing their normal activity or dying (Mitchell et al. 2006).

Physico-chemical treatment relies on the same technical solutions as conventional water treatment, such as screens for the removal of larger material, sedimentation tanks, lagoons, various biological treatment processes like aeration and activated sludge. The various forms of treatment are numerous and rely on different principles, such that different treatment systems can differ greatly through various combinations. By adding chemicals, precipitation and removal of colloidal particles can be achieved through the manipulation of electrical charges and reducing electrostatic repulsion. Other examples of treatment include biological nutrient removal, wherein microbiological processes such as nitrification and denitrification are employed to remove nutrients from the water. As for physical techniques, membrane filtration relies on the use of membranes that treat the water by removing particles and pollutants through straining, depending on their size and the type of membrane. Microfiltration can also be used to physically separate microorganisms from the water (Mitchell et al. 2006).

Disinfection is water treatment involving inactivation of pathogens, such as bacteria or viruses. Normally, many pathogens can be removed by biological degradation and sedimentation with particles to which they are attached, but depending on the desired quality of water and the harvesting of the stormwater, disinfection can be needed. Types of disinfection include the addition of compounds such as chlorine or ozone to the water that are harmful to microorganisms, or deactivating them through UV-light where the radiation harms their ability to reproduce (Mitchell et al. 2006).

McMahon et al. (2008) remarks that the choice of disinfection technique should be chosen through consideration of efficiency in the reduction of microorganisms, cost effectiveness, as well as potential impact on human health and the environment.

A less advanced form of treatment that some systems use are first-flush systems, where the water initially is not collected for reuse when the precipitation starts, as microbiological contamination brought on by bird droppings and various particles such as dust can be swept up with the water (Holm & Schulte-Herbrüggen 2021). The first-flush systems allows for diverting this initial risk factor and ensures that less pollutants make it to storage. Furthermore, filters to prevent leaves and twigs from being collected can be used to filter out such material that it brought with it prior to collection (ibid.).

The fourth component is storage, and in a report from 2006, the Department of Energy and Conservation in New South Wales outlines four different types of storage which could be used for stormwater: Open storage, above-ground tanks, underground tanks and aquifers.

Open storage refers to the storing of water intended for reuse in ponds, pools or other open bodies of water. The benefits include low maintenance and capital costs, although this comes at the cost of them being exposed, although it can serve a dual purpose for recreation. Drawbacks outlined are an increased risk of drowning, breeding potential for pests such as mosquitoes, higher potential of eutrophication and potential aesthetic issues arising from fluctuating water levels (DEC 2006).

Above-ground tanks involve the use of tanks to store the water in, and while this mitigates risks to the public in coming into contact with the water, the capital and maintenance costs are moderately higher. Furthermore, the tanks can be aesthetically problematic for locals (ibid.). Underground tanks are simply storage tanks that have been buried in the soil, and as such they remove the issues of aesthetics and public safety risks altogether, with the drawback of generally having high maintenance and capital costs.

The use of aquifers for storage of stormwater involves the pumping of the water into natural geological formations in the ground, with sufficient permeability to hold the water. The benefits are that it requires little in the way of space above-ground, it is cost effective and furthermore helps prevent saltwater intrusion in the aquifer. Besides requiring suitable geology, however, it also requires pre-treatment of the stormwater in order not to risk contaminating groundwater supply.

The fifth component is distribution. Mitchell et al. (2006) describes it as an important consideration when designing a storm- and rainwater recycling system determined by the spatial area it needs to cover, the density of end uses, and whether or not it should include requirements needed for fire fighting. The density of end uses refers to whether or not it is meant for several or merely one purpose. As to the distribution system itself, whether or not the distribution system is required to adhere to requirements for fire fighting is consequential. If it needs to do so, then the pressure in the distribution system has to be maintained at a high level, with a minimal amount in storage continually to ensure demand can be met at all times.

Furthermore, the stormwater needs to be kept separate from the distribution of potable water to avoid cross contamination and hence health risks. It should also be clearly marked, should taps of said water be accessible that it is not potable. Coloured pipes and warning signs have been used to this end in Australia (ibid.).

Additionally it is also important to take measures to prevent proliferation of bacteria and algae in the distribution system, which can both be done in the treatment stage by thoroughly disinfecting it before entry into the system, but also through other measures such as reducing nutrient levels. Optionally, the distribution system can be drained and flushed after a long period of time in use (ibid.).

Table 2. Summary of examples and challenges associated with the five components of storm- and rainwater recycling systems (Mitchell et al. 2006)

Components:	**Examples:**	**Challenges:**
End-use (intended purpose of the recycled water)	Flushing, washing, irrigation	The water has to be fit for purpose and comply with regulations and due consideration for human health- and wellbeing.
Collection (the means of gathering the water intended for use)	Traditional systems (pipes, gutters and drainage channels), or WSUD (systems designed specifically to harvest stormwater, usually incorporating filtration techniques)	Contamination of the water by metals, nutrients, other pollutants and debris has to be avoided to decrease the need for additional treatment. To achieve efficiency, keeping the collection system clean and minimising water losses is important, as is to maintain the pumps.
Treatment (means of ensuring the quality of the water)	Filtration (biofilters), physico-chemical treatment (filter screens, biological treatment, sedimentation, precipitation) and disinfection (chlorination, UV-treatment)	Depending on the end-use, it is necessary to have complementary treatment steps for redundancy and to remove both particles, pathogens and pollutants.
Storage (keeping the water	Open storage, above-ground	Trade-offs between exposure,

available on demand)	tanks, underground tanks and aquifers	aesthetics, additional pre-treatment, investment and maintenance costs means that the choice is not always clear-cut.
Distribution (system for making the water available to the intended users)	Pipe networks, can be coloured to avoid confusion with the pipes for the drinking water	Build-up of bacteria and algae has to be avoided, and separation with the potable distribution system is necessary. The spatial area, number of end-users and whether or not it needs to be accessible for fire fighting places demands on the pressure of the water. Pumps must be maintained and leakages minimised.

2.4 Scandinavian Climate

Overall, the Scandinavian climate is chiefly temperate, but significantly influenced by the Atlantic and the North Sea, with south-westerly ocean currents providing a milder climate than the latitude might otherwise have suggested. The northern parts of Sweden and Norway are above the arctic circle and as such subject to both cold and prolonged winters, contrary to the milder winters further south. All countries experience varyingly abundant precipitation throughout the year (Britannica n.d.a; Britannica n.d.b; Britannica n.d.c). An overview of the climate in the three countries is provided in Table 3, a climate zone map covering Europe is found in figure 3.

A steady supply of rain throughout the year makes the recycling of storm- and rainwater favourable as far as availability goes, albeit with increasing difficulty the longer that snow lies in place, as it impedes the collection of water.

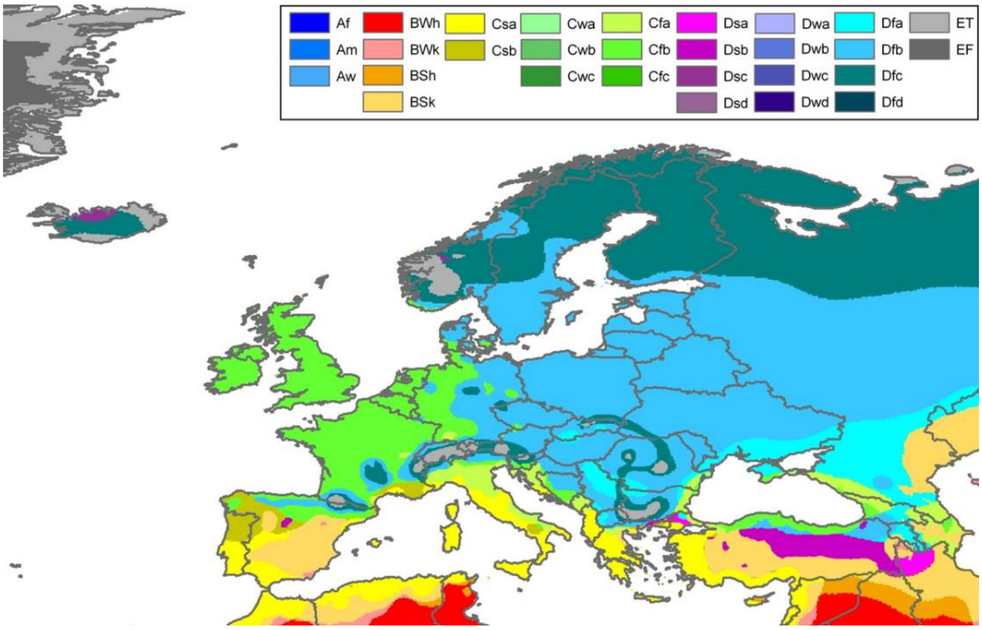

Figure 3. A map of Europe illustrating the different climate zones, using the Köppen system (Peel et al. 2007). Creative commons license.

Table 3. An overview of the climate in Sweden, Denmark and Norway, with average temperatures and annual precipitation averages.

Country:	Sweden	Denmark	Norway
Overview of climate:	Sweden spans two climate zones, with more arctic climate in the north, and more temperate conditions in the south (Britannica n.d.a)	Temperate, albeit fluctuating climate situated where diverse continental and oceanic air masses meet (Britannica n.d.c).	Western Norway is heavily influenced by the North Sea, bringing with it a marine climate of cool summers and mild winters. The eastern part is sheltered by mountains and as such has an inland climate with greater seasonal variation (Britannica n.d.b).
Temperatures:	Between 0 and -5 °C in winter and 17 °C in summer in the south (Britannica n.d.a). In the northern interior, temperatures range between −30 to −40 °C in winter and 17 °C in summer (ibid.).	Temperatures hover around freezing at 0 °C in the coldest months, and go up to average 16 °C in summer (Britannica n.d.c).	Western Norway averages 7 °C throughout the year, with Eastern Norway having both warmer summers and colder winters. (Britannica n.d.b).
Precipitation:	Annual precipitation averages around 600 mm and falls fairly consistently over the year, with the rainiest season being late	Rainfall is fairly consistent throughout the year, although light in spring and winter.	With an annual precipitation average of 2250 mm, Western Norway has very abundant and frequent rainfall (Britannica n.d.b).

	summer and autumn (Britannica n.d.a). Snowfall is common in the south, albeit far more irregularly in the north. Where heavy snowfall is common for up to eight months of the year and snow cover can be present until June (ibid).	The annual precipitation average is at 635 mm, although it ranges from 405 mm in the archipelago of eastern Denmark, to 810 mm in southwestern Jutland (Britannica n.d.c).	In the eastern parts of the country, rainfall averages 760 mm a year (ibid.).

2.5 Existing storm- and rainwater recycling systems in Scandinavia

Below (Figures 4-6) is a series of maps that illustrate where the various storm- and rainwater recycling systems included in this study are situated, with each marker denoting the site of a system. There is a significant concentration particularly in the area of Copenhagen in Denmark, illustrated in Figure 6. Table 4 provides an overview of the pre-selected list of systems.

Table 4. List of the pre-selected systems with their location, end-use, type of water and the status of the systems in regard to this study. Grey represents the stakeholders that were contacted but did not parttake in an interview. **Light green** represents those stakeholders that did parttake in an interview, but did not have all the necessary data. **Deep green** represents those stakeholders that parttook in an interview and had all the necessary data. Light red represents those stakeholders that were not contacted owing to no comparative end-uses.

System:	Location:	End-use:	Type of water:	Status:
Bispeparken	Copenhagen, Denmark	Washing (laundry)	Rainwater	Contacted
Borupgaard Gymnasium	Copenhagen, Denmark	Flushing (WC)	Rainwater	Interviewed, partial evaluation (lacked data for complete MCA)
Celsiushuset	Uppsala, Sweden	Flushing (WC)	Rainwater	Interviewed, full evaluation with complete MCA
Citypassagen Örebro	Örebro, Sweden	Flushing (WC)	Rainwater	Contacted
Gårdhave Straussvej	Copenhagen, Denmark	Artificial lake (recreation)	Rainwater	Not contacted owing to no comparative end-

				uses
Holbæk Laundry Facility	Holbæk, Denmark	Washing (laundry)	Storm- and rainwater	Interviewed, system is still in trial stage and was not fully evaluated
Laholmsbukten VA (LBVA)	Laholmsbukten, Sweden	Flushing (WC)	Rainwater	Interviewed, full evaluation with complete MCA
Nordox	Oslo, Norway	Industrial process water	Storm- and rainwater	Not contacted owing to no comparative end-uses
Nye City	Aarhus, Denmark	Flushing (WC) and washing (laundry)	Storm- and rainwater	Interviewed, full evaluation with complete MCA
Ramboll Headquarters	Copenhagen, Denmark	Flushing (WC)	Rainwater	Interviewed, full evaluation with complete MCA
Sergelhusen	Stockholm, Sweden	Flushing (WC) and irrigation of green areas (recreation)	Rainwater	Interviewed, partial evaluation (lacked data for complete MCA)
Sockenstugan Stora Skedvi	Stora Skedvi, Sweden	Flushing (WC)	Rainwater	Contacted
Sogn Hagelab	Oslo, Norway	Irrigation of green areas (recreation)	Rainwater	Interviewed, partial evaluation (lacked data for complete MCA)
Vaskeri Braband	Aarhus, Denmark	Washing (laundry)	Rainwater	Contacted
Wikholm Anleggsgartner	Bergen, Norway	Flushing (WC), irrigation of green areas (recreation) and cleaning of streets	Rainwater	Interviewed, full evaluation with complete MCA

Figures 4-6 describes the spatial distribution of the pre-selected projects in Scandinavia. For project descriptions detailing each system in turn, see summaries under 4.2 in Table 7 and Table 8. With more detailed descriptions in Appendix A.

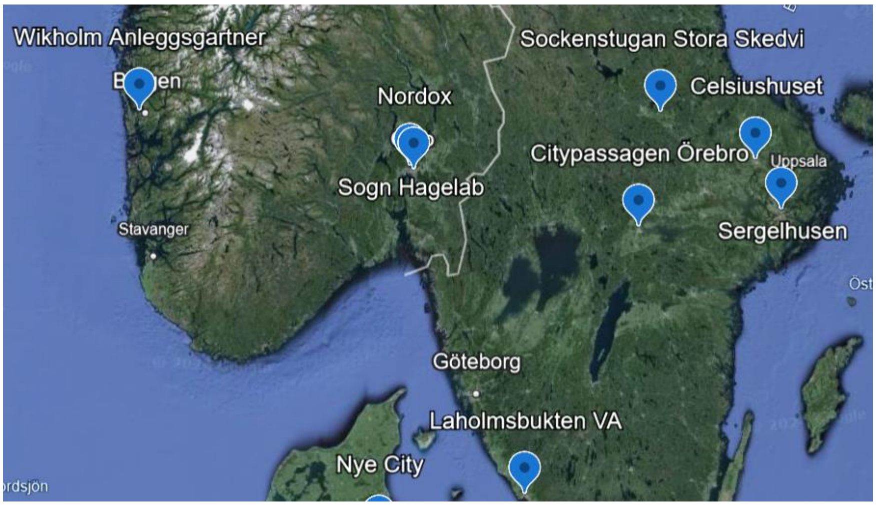

Figure 4. A spatial overview of the systems in Norway and Sweden. Google Earth, © 2023 Maxar Technologies

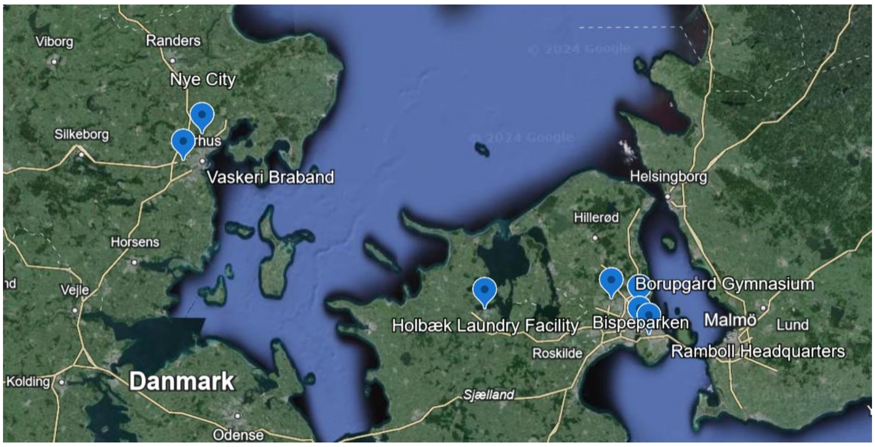

Figure 5. A spatial overview of the systems in Denmark, the systems at Bispeparken, Borupgaard, Gårdhave Straussvej, and Ramboll Headquarters are all situated in Copenhagen, and as such difficult to differentiate on this map. Google Earth, © 2023 Maxar Technologies

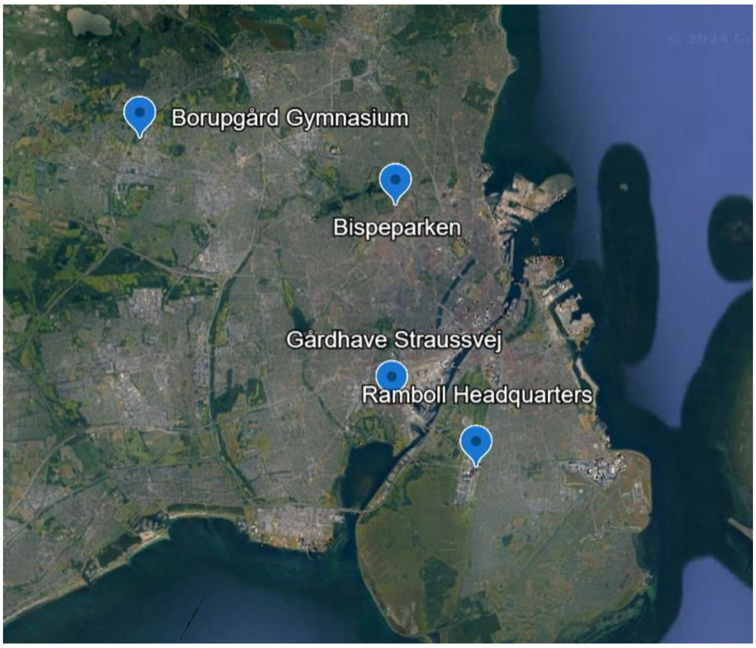

Figure 6. A spatial overview of the system in Copenhagen. Google Earth, © 2023 Maxar Technologies

2.6 Sustainability as a concept in this study

Sustainability is not a simple concept and varies depending on the context. Normally it consists of different aspects, where environmental, social and economic factors are often considered. In terms of technical solutions, however, a technological aspect is sometimes included. In pursuit of sustainability, it is often necessary to have all of these aspects in mind (Drejeris 2019).

Environmental:

The environmental aspects involve the need for a minimal and sustainable impact on the environment, such that natural resources and ecosystems are not continually degraded. This means that renewable resources should not be harvested beyond their ability to replenish, and non-renewable resources should not be depleted faster than the historical rate of the discovery of replacements for said resources. Additionally, waste emissions should be kept within the assimilative capacity of the sinks in the environment, and not cause the environment damage. In the context of climate, this means limiting greenhouse gases to within the planet's ability to cope with them, without changing the climate (Goodland 2002).

Economic:

In practice, a solution could be optimal in practice for humans and the environment, but a solution is not feasible if it is too expensive, which is the essence of economic sustainability. Economic capital needs to be maintained if a project is to succeed and be sustained. Costs for investment as well as operation and maintenance must be weighed in relation to the benefits in order to promote efficiency, and make the most of what resources are available (Goodland 2002).

Social:

Social sustainability involves the engagement, wellbeing, trust and acceptance by local actors towards the project; a technical solution as such is not sustainable if the intended users are not comfortable with it. Furthermore, it must adhere to the local regulations and respect human rights, such that the benefits of the project do not come at the expense of others (Goodland 2002).

An exceedingly important factor as such in regard to water is the health of the users, such that the project does not contribute to illness or other health complications. Even if not intended for human direct or indirect consumption, it is necessary to consider the quality of the water intended for human contact (National Center for Biotechnical Information 2009).

Technological:

Technological sustainability is a fourth pillar of sustainability that places emphasis on the technical solutions themselves, and not merely their results. A sustainable technological solution is generally energy and resource efficient. Furthermore, it must also be available and reliable, meaning that it needs to function as it is intended and be convenient to use. Similarly, it needs to be user-friendly, not requiring maintenance that is not practically feasible (Drejeris 2019).

3. Method

In order to approach the research questions outlined in 1.6, a literature study, interviews with stakeholders and a multi-criteria analysis were conducted, and are outlined in more detail below.

3.1 Interviews

Interviews were conducted with the owners and/or stakeholders of the systems presented under chapter 2.5 and consisted of two parts: one part focusing more on the qualitative aspects, and the second on the quantitative parameters. The qualitative part was aimed at gathering insight into practical experiences with storm- and rainwater recycling in Scandinavia, such as contentment and issues encountered. The quantitative part was focused on data that could be used to evaluate the system's performance, such as energy consumption, investment and operating costs. The questions asked during the interviews can be found in Appendix B.

Stakeholders for most of the pre-selected storm- and rainwater systems were contacted, as per the selection criteria outlined in 1.6. Out of thirteen requests for interviews, three did not respond, whereas one did respond but did not consent to participate in an interview. In total, stakeholders for nine of the pre-selected systems were interviewed. Three separate interviews were however conducted for one of the systems as it had several stakeholders involved in it, for a total of eleven conducted interviews.

3.2 Literature study

The literature study was undertaken to provide sufficient information to grant a wider understanding of the topic and support the study in its conclusions. Chiefly, desk research was utilised to locate reports pertaining to the subject. The database of scientific literature, ScienceDirect, was also extensively utilised. Frequently, sources were identified through having been used by other literature.

The chief focus of the literature study was the current state and conditions of storm- and rainwater recycling in the Scandinavian countries (i.e. Sweden, Norway and Denmark), and whether or not international literature could support the premise that storm- and rainwater recycling could, in theory, be a sustainable source of alternative water.

Another point of focus for the literature study as far as local conditions for storm- and rainwater recycling went was to look for any national targets as to storm- and rainwater recycling, as well as what laws applied, and the local climate. These factors were assumed to be important in regard to storm- and rainwater recycling.

3.3 Multi-criteria analysis

For this study, a multi-criteria analysis was used to provide an overview of how the systems performed in quantitative aspects. A multi-criteria analysis, or MCA for short, can be a robust and flexible methodology that can be employed to evaluate different options according to multiple parameters and criteria, such as cost-effectiveness and environmental impact. There are many different MCA techniques, where applicability depends on what is to be evaluated, the time and data available, as well as factors such as the need for precision (Dodgeson 2009).

Commonly, the MCA is used to list options according to the preference yielded by a set number of objectives, potentially giving valuable support for the decision-maker. Depending on preferences and the nature of the projects analysed, different criteria can be weighted to add particular emphasis to those deemed to be more important than others (ibid.).

In this study the linear-additive model was applied for aggregation of the total score, given the sparse data and that the MCA it was meant to merely help measure performance, rather than being a more comprehensive and in-depth evaluation. It is a simple variant of MCA, useful when one seeks to weigh several different criteria preferentially independent of each other, and uncertainty is not formally built in within the model. It consists of a series of criteria, each assigned a value, and each value potentially multiplied by a weighting factor. These weighted values are then added together to yield a total sum for that option. After conversion to a common scale, these sums are used to measure the different options against each other. As per Dodgeson (2009), the linear additive method can be a robust tool that can be applied to a number of different problems and circumstances, forming a foundation for more in-depth analysis.

Based on the scope of the study as well as what data was available from the answers of the conducted interviews, the following criteria were selected for the comparison of the different storm- and rainwater recycling systems: Energy intensity, carbon emission intensity, cost of recycled water, investment cost per cubic metre of recycled water and availability (illustrated in Table 5).

For investment costs per cubic metre over intended lifespan, Swedish costs for traditional drinking water systems were used to provide a baseline and assumed to provide an adequate approximation for other Scandinavian countries.

Table 5. The parameters used to evaluate the projects in the MCA and how they are defined in the context of this report.

Parameter	Description
Energy intensity	Energy consumption of the system when in operation, relative to how much water it produces.

	Measured in kWh/m^3.
Carbon emission intensity	How much carbon the system emits in operation. Calculated by multiplying the energy intensity of the system [kWh/m^3] with the carbon intensity of the regional grid [gCO_2/kWh]. The carbon intensity of the regional grid is taken from Electricity Maps (2024). Measured in gCO2/m3.
Cost of recycled water	The cost of the recycled water when the system is in operation, disregarding the initial cost of investments. The operating costs [EUR/year] are divided by the amount of water recycled in a year [m^3/year]. Measured in EUR/m^3.
Investment cost per cubic metre of recycled water over intended lifespan	A means of quantifying the investment cost relative to how much water can be theoretically recycled throughout the lifespan of the project. The investment costs [EUR] were divided by the amount of water recycled on an annual basis [m^3/year] multiplied with the intended lifespan [year]. Measured in EUR/m^3.
Availability	Denotes what fraction of the year that the system produces recycled water. As such, even if the system is functional and could theoretically produce water, but it does not owing to e.g. a lack of rainfall or the presence of snow, then it does not count towards availability. How much water the system could produce or what fraction it could replace drinking water was not factored in, merely how frequently it could produce water. Measured in %.

These five parameters were then assigned values on a scale of 1 to 5, with the average value of 3 aimed, except for availability, at representing the literature values for traditional drinking water systems. These values in turn had the aim of representing the relative performance of the system for each parameter, effectively a kind of performance rating. E.g. a system with the value of 2 for energy intensity is assumed to have a lower energy intensity than drinking water, whereas a system with a value of 1 for the same parameter could be deemed to have a much lower energy intensity than drinking water.

Higher values, 4 and 5 respectively, indicates a system with a worse performance relative to drinking water. Or, in the case of availability, a worse performance relative to other storm- and rainwater recycling systems.

The values of each examined storm- and rainwater recycling system were then weighted and added together to a total sum. As to help differentiate different projects, the spans for various values beyond the average value of 3 were assigned based on the data available. This was to avoid using spans that were too broad that just resulted in systems with drastically different performance being assigned the same values.

The MCA was aimed at providing an indication of how the projects performed quantitatively, particularly relative to each other and a theoretical 'Average System' that uses drinking water, albeit with an availability of an average storm- and rainwater recycling system drawn from what could be seen in the collected data.

The decision to not draw literature values for drinking water for availability and use that as the average value of 3 was an assumption that the near-constant availability of drinking water would negate any differences between the examined systems as they use an intermittent supply of water. Therefore, setting ~100% as the average would mean that the MCA would be less sensitive to performance between different storm- and rainwater recycling systems.

3.3.1 Compilation and weighting

The raw data was first collected from the interviews and compiled such that an overview could be provided. Then functional units were calculated as described in 3.3.2. Weighting factors are detailed in Table 6.

Owing to the investment cost being repeatedly cited as a barrier for installation by the stakeholders, investment costs per recycled cubic metre over intended lifespan were weighted with a comparatively high factor of 2.

As for the carbon emissions, being dependent on the regional grid and energy intensity, were weighted with a factor of 0.5 owing to that the emissions in and of themselves were not directly caused by the design of the system. Furthermore, the scope of the systems were such that the emissions were not to be deemed considerable. On the upper estimates of potential emissions from Nye, the water system only totalled roughly 480 kg CO_2/year (with 7300 cubic metres annually, and an estimated 66 gCO_2/m^3).

Table 6. Weighting factors used for the different parameters.

Parameter	Weighting Factor
Energy intensity	1
Carbon emission intensity	0.5
Cost of recycled water	1

Investment cost per cubic metre over intended lifespan	2
Availability	1

3.3.2 Calculations of parameters for the MCA

Investment costs are estimates based on stated investment costs by the stakeholders, average exchange rates between currencies in recent years, and an inflation-adjusting tool from the Swedish Bureau of Statistics (Statistics Sweden 2024). To enable comparison, the total investment costs were adjusted for inflation since the systems were taken into operation at different times.

Lacking a tool to adjust Euro to inflation, given the influence of the European Central Bank on Scandinavian monetary policy, the assumption was made that the inflation adjustment factor for SEK (Sweden Statistics 2024) would give an adequate estimate for estimating costs for the projects in prices for 2024, before conversion to EUR. The choice to work with EUR was to work with a currency to which all the Scandinavian currencies have close ties, and as such provide a better overview when comparing projects in different countries.

Abbreviations:

- Energy Intensity (EI)
- Carbon Emission Intensity (CEI)
- Cost of Recycled Water (CRW)
- Investment cost per cubic metre of Recycled Water over intended lifespan (IRW)
- Availability (A)
- Inflation Adjustment Factor (IFA)
- Currency Exchange Rate (CER)
- Estimated/intended Lifespan of system (L)
- Recycled Water per year (RW)
- Carbon Intensity (CI)
- Energy Consumption (EC)
- Operating costs (OC)
- Investment Costs (IC)
- Relative Weight Factor (RWF)

Inflation-adjusted cost in EUR from Scandinavian currency, using SEK as example:

$$Cost\ [EUR] = Cost\ [SEK] \times IFA \times CER\ \left[\frac{EUR}{SEK}\right] \text{ (Sweden Statistics 2024)} \qquad (1)$$

In the absence of any other operating costs known to the owner of the system, and knowing the energy consumption, the assumption was made that the cost of the electricity to run the system was equal to the operating costs.

In this case, the energy consumption was merely converted into an energy cost, and the same methodology/equation (1) was applied.

$$EI\ \left[\frac{kWh}{m^3}\right] = \frac{EC\ [\frac{kWh}{year}]}{RW\ [\frac{m^3}{year}]} \tag{2}$$

$$CEI\ \left[\frac{gCO_2}{m^3}\right] = EI\ \left[\frac{kWh}{m^3}\right] \times CI\ \left[\frac{gCO_2}{kWh}\right] (Electricity\ Maps\ 2024) \tag{3}$$

$$CRW\ \left[\frac{EUR}{m^3}\right] = \frac{OC\ [\frac{EUR}{year}]}{RW\ [\frac{m^3}{year}]} \tag{4}$$

$$IRW = \left[\frac{EUR}{m^3}\right] = \frac{IC\ \ [EUR]}{RW\left[\frac{m^3}{year}\right] \times L\ [year]} \tag{5}$$

Multi-criteria analysis:

$$Total\ sum = (EI + 0.5CEI + CRW + 2I + A) \times RWF \tag{6}$$

The relative weight factor was set at $RWF\ = \frac{15}{16.5}$, and included as to ensure that the average sum for both weighted and non-weighted total sums were equal and made comparison between them easier.

3.3.2.1 Calculations of investment costs for traditional drinking water systems

For traditional drinking water systems, two separate calculations were performed to create a span capturing the large variations of cost that can be found in drinking water systems, depending on location and what water was used for production. The total investment costs of traditional drinking water systems were assumed to comprise the investment costs for both the production plant, where the water is treated, as well as the initial investment cost for the distribution network needed to bring the water to the consumer.

Separately, the two configurations represent two theoretical scenarios intended to encompass, using the average values available, the cheapest and most expensive traditional drinking water systems. With the assumption made that the span captures what one can expect the investment costs of traditional drinking water systems to be, per cubic metre of produced drinking water, over the technical lifespan of the system. The two scenarios have been outlined in Table 7.

High-end and low-end cost scenarios:

Table 7. Summary of theoretical low-end and high-end investment costs for drinking water production (Svenskt Vatten 2023b).

Low-end cost scenario	High-end cost scenario
Drinking water production plant: Groundwater as source at 5000 SEK/PE, technical life expectancy at 100 years.	*Drinking water production plant:* Surface water as source at 10000 SEK/PE, technical life expectancy at 50 years.
Drinking water distribution network: Length of the total distribution network at 6.1 metres/PE, of which 42% constitutes drinking water distribution, the rest being for sewage and drainage.	*Drinking water distribution network:* Length of the total distribution network at 62.5 metres/PE, of which 42% constitutes drinking water distribution, the rest being for sewage and drainage.

As per Table 7, the low-end, or cheapest configuration, was used to provide a lower limit for investment costs. Groundwater was used as a source as it requires less intensive treatment, a longer technical life expectancy of 100 years was assumed for the drinking water production plant. Furthermore, the length of the distribution network per person was assumed to be on the low end of that which was listed by Svenskt Vatten (2023b), equivalent to 6.1 metres, and usually found in large cities.

For the high-end or most expensive configuration, as per Table 7, surface water was assigned to be used as a source as it requires more expensive treatment, and a lower technical life expectancy of the drinking water production plant at 50 years. With the lower technical life expectancy as to make the system more expensive, relative to the number of years it is in operation such as in the low-end cost scenario. The length of the distribution network per person was assumed to be the upper end of what was stated by Svenskt Vatten (2023b), of 62.5 metres per person, which was found in sparsely populated areas.

For both distribution system calculations, a factor of 0.42 was multiplied to represent the fraction of the distribution system that was for drinking water, and as such excluded pipe network pertaining to sewage and drainage. This was drawn from the report from Svenskt Vatten (2023b), where the drinking water distribution system constituted some 85 170 km out of 203 425 km in total, with the total having drinking water, stormwater and wastewater all included.

Formula for investment cost for drinking water production plant:

Abbreviations:

- Investment cost per cubic metre of Drinking Water over intended lifespan for production plant (IDW1)
- Investment cost per Population Equivalent for production plant (IPE1)
- Investment cost per cubic metre of Drinking Water over intended lifespan for distribution network (IDW2)
- Investment cost per metre for Distribution Network (IDN2)
- Length of distribution network per Population Equivalent (LPE2)
- Consumption of water per Population Equivalent and year (CPE)
- Inflation Adjustment Factor (IFA)
- Estimated Lifespan of Production Plant (LPP)
- Estimated Lifespan of Distribution Network (LDN)
- Currency Exchange Rate (CER)
- Drinking Water Fraction of distribution network (DWF)

$$IDW1\left[\frac{EUR}{m^3}\right] = \frac{IPE1\left[\frac{SEK}{PE}\right]}{CPE\left[\frac{m^3}{PE\times year}\right]\times LPP\,[year]} \times IFA \times CER\left[\frac{EUR}{SEK}\right] \times DWF \quad (7)$$

Low-end investment cost for drinking water production plant:

$$\text{Low end: } 0.10\left[\frac{EUR}{m^3}\right] = \frac{5000\left[\frac{SEK}{PE}\right]}{0.14\times 365\left[\frac{m^3}{PE\times year}\right]\times\ 100\,[year]} \times 1.2 \times 0.087\left[\frac{EUR}{SEK}\right] \times 0.42$$

High-end investment cost for drinking water production plant:

$$\text{High end: } 0.41\left[\frac{EUR}{m^3}\right] = \frac{10000\left[\frac{SEK}{PE}\right]}{0.14\times 365\left[\frac{m^3}{PE\times year}\right]\times\ 50\,[year]} \times 1.2 \times 0.087\left[\frac{EUR}{SEK}\right] \times 0.42$$

Formula for investment cost for distribution system:

$$IDW2\left[\frac{EUR}{m^3}\right] = \frac{IDN2\left[\frac{SEK}{m}\right]\times LPE2\left[\frac{m}{PE}\right]}{CPE\left[\frac{m^3}{PE\times year}\right]\times LDN\,[year]} \times IFA \times CER\left[\frac{EUR}{SEK}\right] \times DWF \quad (8)$$

Low-end investment cost for distribution network:

$$\text{Low end: } 0.37\left[\frac{EUR}{m^3}\right] = \frac{7000\left[\frac{SEK}{m}\right]\times 6.1\left[\frac{m}{PE}\right]}{0.14\times 365\left[\frac{m^3}{PE\times year}\right]\times\ 100\,[year]} \times 1.2 \times 0.087\left[\frac{EUR}{SEK}\right] \times 0.42$$

High-end investment cost for distribution network:

$$\text{High end: } 3.75\left[\frac{EUR}{m^3}\right] = \frac{7000\left[\frac{SEK}{m}\right] \times 62.5\left[\frac{m}{PE}\right]}{0.14 \times 365\left[\frac{m^3}{PE \times year}\right] \times 100\,[year]} \times 1.2 \times 0.087\left[\frac{EUR}{SEK}\right] \times 0.42$$

Total investment cost per cubic metre of drinking water:

Low-end: 0.19 + 0.37 = 0.47 EUR/m^3

High-end: 0.41 + 3.75 = 4.16 EUR/m^3

3.3.2.2 Project-specific calculations

For some projects, the necessary information was not provided outright, and additional calculations had to be conducted from what data and information was available. The assumptions and estimates made are compiled in Table 8. These are covered in more detail in Appendix C.

Table 8. A summary of the assumptions and estimates made during the calculations pertaining to the MCA.

Project	Assumptions
Celsiushuset	The water recycled was estimated as 60% out of an estimated annual consumption of 1570 cubic metres for flushing on an annual basis in the building (Söderqvist 2021). operating costs were estimated to be represented by the cost of electricity for the pumps, equal to some 0.149 EUR/kWh with power prices and electricity tax added together (Uppland Energi 2024; Swedish Energy Market Bureau 2024).
LBVA	The pumps, working at an effect of 0.55 kW, were estimated to operate with a flow capacity of 2.7 m^3/h as per an employee of the manufacturer Xylem[4]. operating costs were estimated to be represented by the cost of electricity for the pumps, equal to some 0.11 EUR/kWh with power prices and electricity tax added together (Elbruk 2024; Swedish Energy Market Bureau 2024).
Nye	Only operating costs assumed to be strictly related to the water recycling system, as best as the project could determine from the list of expenditures, were included. This excluded operating costs such as rent of what was presumed to be the land upon which the city had been built.

3.3.4 Sensitivity analysis

The sensitivity analysis was undertaken through a twofold approach to shed light on how the results were affected through changes to how the method was implemented. Firstly, the weighting factors for the MCA were removed to render all criteria equal. Secondly, a separate MCA was conducted where the spans for the average value of 3 were adjusted to represent a wider span, one that ranged from the highest and lowest numbers associated with drinking water found in the literature study.

This was to see how the weighting influenced the results, as well as to see how it changed if one included the more expensive and upper-limit traditional drinking water systems. Availability in this second iteration was altered such that a higher availability would be needed to reach higher values, e.g. the average value of 3 needed an availability of 80-94.9%, as opposed to 50-89% in the first iteration. The choice to be more stringent on availability was to provide a better comparison with traditional drinking water systems generally available at all times.

4. Results

4.1 Literature study

4.1.1 Storm- and rainwater recycling in Scandinavia

Contrary to nations facing decreased precipitation and severe drought as a result of climate change and local meteorological factors, Scandinavian nations face challenges from more but irregular precipitation. In a report by the Swedish Government (2007), it was concluded that the shifts in precipitation brought on by climate change will bring more days of heavy rainfall and longer dry periods in Scandinavia. The increased intensity of rainfall will pose challenges for existing infrastructure, and lead to heightened risk for flooding through the overwhelming of drainage infrastructure. Downpours causing sewer systems and surface water to overflow can flood basements and discharge sewage into natural waterways. The increased risk of heavy rainfall necessitates more mitigating efforts to decrease the strain on sewage and drainage systems, given that the report states that it was already a major problem by the time of its writing (ibid.).

4.1.1.1 Storm- and rainwater recycling in Sweden

Literature on storm- and rainwater recycling in Sweden was sparser than that of Denmark, but considerably more common than that which could be found for Norway, consistent with a theme of Sweden trailing Denmark but leading Norway in the field of storm- and rainwater recycling.

Relevant to the topic of storm- and rainwater recycling was the current state of water use in the respective countries overall, as a means of gauging the potential of recycled water for the uses examined in this study. In 2020, Sweden’s total water use was 3 074 697 000 m^3. Out of this, 18.5% was used by households, 68.2% for industrial purposes, and 3.3% for agriculture (SCB 2021). As such, some 6% of Sweden’s total water consumption is used for flushing and washing by households alone, not counting those same uses in other areas of society, like at schools or workplaces.

As per Svenskt Vatten, Swedish households use 140 litres per individual and day, of these 140 litres, 15 litres are used for washing, and 30 litres are used for flushing which is in total 32% of an average household's consumption of water (Svenskt Vatten 2021).

The most expansive literature on the topic of storm- and rainwater recycling in Sweden that was found during this study, was a Swedish study from 2021, written by Holm and Schulte-Herbrüggen. The study evaluated the recycling of storm- and rainwater in Sweden as part of a wider report on water-saving methods, on behalf of Swedish municipalities. The report states that rainwater is generally of high quality and as such it makes for a good resource that does not inherently require extensive treatment, but the manner of how it is collected is important as it risks being contaminated in the process, although first-flush systems are sometimes used (Holm & Schulte-Herbrüggen 2021).

What storm- and rainwater recycling is used for in Sweden was covered by Holm and Schulte-Herbrüggen (2021), wherein they studied the prevalence and end-uses of the recycling of rainwater over several municipalities. In total, 92 individuals answered. The most common application was watering of non-edible vegetation and irrigation of crops, with the most prevalent being the former. A handful, three respondents, used it for other purposes such as flushing, showering and the washing of hands. On average, the respondents saved some ten litres of water a day. The chief challenges to these systems were uneven precipitation, lack of storage, debris and insect larvae in the water and high costs. Holm and Schulte-Herbrüggen (2021) therefore stressed the importance of filter systems, sufficient storage and drainage systems in the event of storage overflowing.

Some 62% of respondents professed being open to expanded use of rainwater to other applications in households, with some 16% being hesitant. The reasons behind hesitation were mainly the technical solution itself, the necessity of installing new pipe systems, uneven access to water and a lack of knowledge as to how it would be done in practice (ibid.).

With the low cost of drinking water in Sweden, Holm and Schulte-Herbrüggen (2021) remarked that the chief motivations for installation of storm- and rainwater recycling or other water-saving measures are not economical. Rather, the low cost of water means that it is difficult to have these measures pay for themselves merely through savings in water. Environmental consciousness, water shortages, an interest in safeguarding freshwater resources, a desire to appear as environmental frontrunners and for marketing purposes are all reasons for why storm- and rainwater recycling systems have been installed in Sweden.

The desire for sustainability was a significant motivator for another of the few Swedish studies on the subject, a case study for a potential rainwater recycling system for Ringdansen, a residential area in the city of Norrköping in Sweden. In the study by Villareal et al. (2005), rainwater recycling for the uses of flushing, laundry, irrigation of green areas and car washing was analysed by means of a computer model and evaluated based on the water saving efficiency of the rainwater recycling system. The study, in its conclusions, emphasised sufficient storage ideally combined with low water consumption appliances for the highest water saving efficiency. The size of the needed storage was correlated with the size of the collection area, where a collection area of 60 000 m^2 and 20 m^3 storage tank would save as much water as a storage tank of 40 m^3 with a 40 000 m^2 collection area (ibid.).

The water savings from using recycled rainwater were considerable under the local conditions, even considering the inhibiting factor of snow in the months of December-February. Villareal et al. (2005) estimated that 30-60% of the water demand could be saved depending on the configuration of the rainwater recycling system, with some 60% of the water demand for irrigation during the summer saved, with the authors remarking that these savings were in line with other storm- and rainwater recycling systems in case studies that they had reviewed. Finding that rainwater recycling could potentially be a sustainable source of alternative water in Sweden.

A factor that affects the sustainability of storm- and rainwater recycling, as alluded to above, is the relatively cheap cost of drinking water in Sweden that the recycled water has to compete with. However, as per the Swedish trade association representing the municipal water sector, water levies are however expected to increase drastically owing to factors such as high energy costs and inflation (Svenskt Vatten 2023a). There is also a backlog of necessary investments in expanding and renovating old infrastructure which will put increasing pressure on the price of water. These investments are needed in order to meet new demand, adapt to climate change, and amend unreasonable differences between different municipalities. All of which contribute, and are expected to contribute to, an increase in the costs of water, although they are still expected to remain at fairly low levels internationally (ibid.).

Current forecasts for investment needs for the municipal utility sector is estimated by Svenskt Vatten (2023b) to be around 31 billion SEK, or around 3 billion Euro on an annual basis. Out of these, 5 billion SEK is needed for drinking water production facilities, and 17 billion SEK on the distribution network. Furthermore, the speed with which the distribution network is being replaced would mean that some 200 years would be necessary to renew it. Water levies from capital expenditures alone are estimated to rise some 105%, and by 2027, capital expenditures on infrastructure will rise to be half of the total expenditures for water utilities. By 2035, those same capital expenditures are further estimated by Svenskt Vatten (2023b) to have doubled.

4.1.1.2 Storm- and rainwater recycling in Denmark

Denmark appears a frontrunner in storm- and rainwater recycling, something illustrated by the literature on the subject, relative to Sweden and Norway. There are a number of studies, and the topic at large appears to have garnered more interest than elsewhere in Scandinavia, some dating back over two decades.

In a study from 1999, the authors Mikkelsen et al. from the Technical University of Denmark concluded that the Danish potential for rainwater collection from rooftops at the time was equivalent to some 229 million m^3/year. This was equivalent to 24% of the mostly groundwater-based production of drinking water. From the roofs of households alone, some 64.5 million m^3/year could be collected for uses such as the washing of clothes and flushing. The 64.5 million m^3/year was equivalent to 68% of the Danish use of water for flushing at that time, or 22% of the total household consumption of drinking water, although only 7% of the total Danish use of drinking water nationally. The study concluded that, at that time, there was no environmental or economic reason to pursue a systematic collection and use of rainwater on a national scale. Instead, it was better viewed through a more local context.

The Danish water consumption was 105 litres per person and day as per a report from 2022 by DANVA, the Danish Water and Wastewater Association, and has been on a downward trend since 1987 (DANVA 2022).

Relevant to the need for storm- and rainwater recycling is the freshwater supply it is intended to, to an extent, replace. In Denmark, this is a more pressing challenge than Sweden and Norway. Groundwater resources, upon which Denmark exclusively relies for drinking water, have however come under increasing strain since the study written in 1999, a problem exacerbated by pollution where various pollutants such as Per- and Polyfluorinated Substances (PFAS) and pesticides have infiltrated the aquifers. This is especially a problem in more heavily populated regions with industry (International Water Association 2022).

The most comprehensive Danish report that was found during the literature study was a study from 2015, conducted by a wide range of authors from different Danish universities delved into sustainable urban drainage systems. Even though the report states that while Denmark has not yet had any serious issues with water scarcity, predictions for climate change do indicate that prolonged periods of drought periods would become more prevalent (Hoffman et al. 2015).

The authors make the case that cities faced with increased water scarcity and population growth can make use of rainwater harvesting and recycling to reduce their need for drinking water. Thus ensuring a water balance is kept by replacing drinking water for certain uses with recycled storm- and rainwater. An innovation consortium, named ‘Cities in Water Balance’ has been working towards finding solutions that jointly tackle flood and drought management. By collecting rainwater during heavy rainfall, or direct or indirect use, the pressure on existing infrastructure is decreased, and more water is available during periods of drought. Other aspects of establishing a water balanced city includes the increasing infiltration, evaporation and amending leakages in the drinking water distribution system (ibid.).

Another challenge that is being exacerbated by climate change is flooding. Denmark has already faced more severe rainfall which has contributed to flooding, causing damage to homes and infrastructure alike. The authors make the case for more intelligent water management than merely replacing existing pipes with larger ones, instead, they advocate for a strategy that detains rainwater in urban structures and distributes it to other areas, taking the pressure off the drainage system. With the report stating that more and more Danish cities are looking at sustainable urban drainage systems, the authors also make the case that the best solutions are those that work towards tackling several challenges concurrently (Hoffman et al. 2015).

A number of solutions to excess rainwater and retention of water are mentioned, including roadside infiltration beds, green roofs, ensuring separate drainage systems for stormwater and wastewater and subsurface infiltration beds. By integrating green areas in urban environments, for instance, contributions can be made to biodiversity and recreation, while at the same time the risk of flooding is decreased (ibid.).

As to the prevalence of such systems, a report from Brudler et al. (2019) of the Danish Technical University states that a number of systems for stormwater recycling is already in operation. The most common uses for these being to supply water for toilets and washing machines. Some places in Denmark have taken things a step further, with stormwater recycling systems for flushing and washing having been mandated during the construction of a new residential area in Stenløse Syd.

Much like in Sweden, investment needs will put upwards pressure on drinking water prices. As per a report from DANVA (2023), there is a significant need for investments to cope with the effects of climate change and larger rainfall events as well as the green transition, on top of what is already being spent. Although this varies between different utility companies. It was further stated that as to ensure stable prices, more investments were likely to be financed through loans. Forecasts were made that in the short term, the cost could rise to approximately 1.38 Euro per delivered cubic metre of water to consumers as of 2023, from below 1 Euro per delivered cubic metre in the previous decade. The report also makes note of ageing infrastructure as a challenge faced by the Danish water sector (ibid.)

4.1.1.3 Storm- and rainwater recycling in Norway

Norwegian literature on the use of storm- and rainwater appeared sparser than its peers in Sweden and Denmark, with this report not managing to locate equivalently broad reports as to the state of stormwater recycling in Norway. Although there is information as to individual projects that have been carried out, which will be evaluated in this report.

As per Norsk Vann, a trade association akin to Svenskt Vatten, the average Norwegian uses 140 litres of water daily. On the national level, 42% of the national water consumption is done by households, 2% by holiday homes, and 25% for industrial purposes. An additional 31% of produced drinking water is lost due to leaks in the distribution network (Norsk Vann 2018). Of the drinking water that is produced, some 90% of the water supply is surface water, and only 10% groundwater (Norsk Vann 2024).

In contrast with Denmark that faces threats to its water supply, Norway has almost the opposite challenge. Norway, owing to the prevalence of westerly winds that sweep in over its long coast and the moist air from the North Sea, has abundant rainfall with some of the wettest regions in all of Europe. Here, precipitation can exceed 3500 mm on an annual basis (World Bank Climate Knowledge Portal 2021). Stockholm, in comparison, had an annual precipitation of around 555 mm between 1894 and 2005 (SMHI 2006).

There does appear to be some interest towards storm- and rainwater recycling in Norway, as evidenced by a research grant from the Norwegian Research Council. The grant encompassed some 0.82 million NOK for a period between 2021-2023, for a study aimed at enhancing rainwater harvesting and innovative wastewater management in Norway. As to the segment pertaining to rainwater, the two chief queries that the project funded by the grant, called ENRICH, aims to answer is; whether or not the storm- and rainwater resources can be safely collected and used for different purposes. It also aims to answer how storm- and rainwater can be transitioned from a problem into becoming a resource in urban catchments (Norwegian Research Council 2023).

Besides research grants, there are also storm- and rainwater recycling systems already in operation, with three of them being mentioned in this report. The recycling of storm- and rainwater for flushing, the sweeping of streets and process water are established uses (Nordox n.d.; Wikholm n.d.; Sogn Hagelab n.d.).

Much like in Sweden and Denmark, Norway faces a significant backlog of necessary investments in its traditional water infrastructure. The system as a whole is valued at over 1200 billion NOK (106 billion EUR), and the magnitude of it will impose large costs over the coming years owing to several challenges. The main reasons are stricter requirements on water, sewage and sludge, challenges stemming from climate change, an expansion of water and sewage to a larger population and the prevalence of old and crumbling infrastructure that needs to be replaced (Norsk Vann 2024).

With the abundant rainfall described above, a significant challenge that Norway faces that adds to their investment needs, is stormwater. A challenge being aggravated by climate change. Damage to infrastructure arising from stormwater in Norway is currently estimated as of 2024 to range between 1.6-3.6 billion NOK a year, with estimates that it may double over the next 40 years (Norwegian Directorate of Building Quality 2024).

4.1.2 National storm- and rainwater recycling strategies

This study examined whether or not, even if there were no concrete regulations, there were any stated ambitions or strategies for the recycling of storm- and rainwater in Scandinavia. Broadly, there does not appear to be any concrete targets or strategies for the recycling of storm- and rainwater on the national level in Scandinavia. In recent years, there has been an increased desire to view stormwater as a resource and integrate nature-based solutions, but the focus on the use of stormwater has been limited. With more emphasis placed on challenges arising from altered precipitation patterns and major rainfall events, rather than seeing a potential benefit in and of itself in the recycling of stormwater.

The Swedish Government tasked the Swedish EPA to carry out a study, wherein they are to make proposals for how to better engage with stormwater management in future. Whilst no targets have been established yet pertaining to the reuse of stormwater, the study is to be concluded by 2025 and as such that may be subject to change. In that which has already been established, it is stated that stormwater is to be engaged with as a resource in the future, and not relegated to merely being 'waste' in need of disposal. It is furthermore to be delayed as near to the source as possible and treated if need be. Nature-based solutions, dual in their purpose of creating green areas and managing stormwater, are recommended by the EPA in their proposal for a strategy (Swedish Environmental Protection Agency 2024b).

During this study, no comprehensive strategy or targets was found on the Danish national level as far as stormwater is concerned. Instead, strategies such as the Danish Climate Adaptation Plan involves stormwater management as opposed to recycling. The report advocated for green wedges, in the form of basins and canals, to increase retention and infiltration in the events of heavy rainfall (Danish Government 2012).

Norway's strategy towards stormwater, faced with increasing challenges arising from climate change and increasing urbanisation, is based on a 3-step solution. The first step being evapotranspiration and infiltration at the source, as per the Water Resources Act. The second step involves the dampening and delay of the stormwater in the event of very significant rainfall, and the third step being the safe diversion of the excess water through defined floodways (Klima2050 2022)

4.1.3 Legal framework of storm- and rainwater recycling in Scandinavia

There is no uniform or expansive legal framework in Scandinavia that regulates the recycling of storm- and rainwater, instead, it is regulated at varying degrees of clarity at chiefly the national level.

4.1.3.1 European Union

The European Union established regulations concerning water reuse in 2020, with the motivation that Europe's freshwater supply is coming under increasing pressure from droughts and a warmer climate. The regulations establish a framework for the harmonised minimum water quality and monitoring requirements for the safe reuse of urban wastewater intended for agricultural irrigation. Furthermore, it has provisions for risk management concerning environmental impact, health safety standards and transparency. Permitting requirements for the reuse of urban wastewater are also included. (The European parliament's and council's regulation 2020/741).

The regulations apply to urban wastewater, previously defined as either domestic wastewater from households, industrial wastewater, run-off rainwater or a mix between them (The European parliament's and council's directive 1991/271).

Although pertaining to rainwater run-off as part of the European Union's definition of urban wastewater, the recycling of stormwater for non-potable purposes is not covered by the current iteration of European law, the regulations introduced in 2020 pertaining to water use having come into force during 2023 (European Commission 2023).

The lack of clarity in established legal frameworks can also be found at the national level, where certain uses of recycled storm- and rainwater fall into grey legal areas. This forces courts and authorities to rely on other legislation not aimed specifically at regulating storm- and rainwater recycling when evaluating the legality of storm- and rainwater recycling systems.

4.1.3.2 Sweden

The legal framework for the recycling of storm- and rainwater in Sweden is not fully established, and there exists no laws that specifically regulate this application of it in the laws pertaining to general water services (2006:412). Stormwater within zoning plans is regulated as wastewater as per the 9 kap. 2 § and 7 § of the Swedish Environmental Code (1998:808) as an environmentally hazardous activity and requires either a permit or a notification. The exception to this is if the stormwater is diverted only on behalf of a single or a handful of properties.

Storm- and rainwater recycling is also encompassed by the regulations of hazardous activities and health protection (FHM), the 13 § and 14§ of the FHM (1998:899). FHM 13 § and 14§ specifies that the installation of new toilets, or the connection of a new sewage unit to which multiple toilets are to be connected, requires permits (ibid.).

Because of the lack of a comprehensive framework, several systems have been evaluated on a case-by-case basis. According to Svenskt Vatten, the use of rainwater for flushing has not resulted in any need to seek permits from the authorities, given that it is merely a matter of installations taking part within the same building that was already connected to the sewage system. In the case of the use of recycled water for irrigation of parks by the local water utility company, past such applications were initially unclear as to whether or not a permit would be necessary, but no objections were raised from either the county or the municipality (Johansson et al. 2022).

Another example of how a system has been evaluated by existing laws pertains to the irrigation of public parks and other green spaces. The system that was evaluated in an environmental court did not exist in the original zoning plans submitted for the water system in the area nor was it carried out by the local water utility company, VA SYD, responsible for the distribution and drainage systems. As the system was novel, the question of whether or not a permit or notification was needed was unclear, as VA SYD held no objections. In short, the lack of (ibid.).

A legal issue with some lack of clarity in general, and not pertaining to a specific case, is the process of irrigation with storm- and rainwater itself, as the general rules of consideration of 2. Chapter in the Swedish Environmental Code (1998:808) apply, which necessitate that the activities do not cause harm or undue disturbance to those that might be affected by it. Potential microbial risks, such as e. coli could become a factor in how the irrigation itself is carried out. The act of spraying the water could spread bacteria through aerosols, a risk that can be mitigated by instead opting for the spreading of the stormwater through a hose (Johansson et al. 2022).

Another question did arise on a legal basis for new, innovative technologies, where recycled stormwater was to be used for irrigation of plant beds, also called rain gardens. The dual-purpose of the rain gardens, aimed both at enhancing recreation by contributing to green space, but also for stormwater management. The gardens intended to both delay and treat stormwater, even as they took some of the strain off the drainage system by draining some of it for their own use. This dual-use, and the incomplete regulations, means that it is not entirely clear what precisely to define the plant beds as and in turn, who is responsible for it. If the treatment and management of stormwater is secondary, then responsibility should fall on someone other than the head (huvudman) of water and sewage management as per Swedish regulations. As such, Svenskt Vatten stressed the need for properties and the municipalities to coordinate and agree on who is responsible for what in matters of dual purposes, absent a clearer legal framework (Johansson et al. 2022).

4.1.3.3 Denmark

Storm- and rainwater, from rooftops, roads and other impermeable areas has been designated by the Danish EPA as having both a large potential for supply and also limited treatment needs, therefore being suitable as a secondary water source (Danish Environmental Protection Agency 2014). The Danish Technical University, in guidelines for reuse, recommend that only simple filtration techniques are necessary for not-potable use (Faldager et al. 2012).

Besides a greater emphasis on storm- and rainwater recycling from the government than some contemporary nations, there are examples from Denmark showcasing such strategies being employed in practice. One example of this is Stenløse Syd, where the installation of rainwater harvesting for the purposes of flushing and washing was mandated during the development of a new residential area (Brudler et al. 2019).

The Danish legal requirements for the reuse of rainwater are very strict, which means that those wishing to make use of it need to ensure to comply with safety standards and take care with the design. One requirement is that the rainwater should not come into contact with drinking water at any point. Furthermore, there must be a physical gap between the two systems, and a back security valve that prevents the drinking water from having any contact with the rainwater. The storage tank must be dimensioned with regard to the intended consumption of water, the quantity of runoff from collection, as well as the residence time of water in the tank. The latter to prevent microbial growth in the storage tank (Hoffman et al. 2015).

Rainwater recycling in Denmark is regulated by the decree on water quality and supervision of water supply facilities (BEK no 2361 of 26/11/2021), the §3 and §5 in particular. Rainwater collected from rooftops for the purposes of WC flushing or washing clothes is exempted in §5 from other demands that normally apply in §3 as to safety measures for water quality. Installations must however be carried out in accordance with recommendations from the Technological Institute. Furthermore, it may not be used in places where very sensitive groups may be exposed to the water, such as children under 6, hospitals and nursing homes. It is also necessary for the owner to clearly inform all users about the system.

Although recycled storm- and rainwater can be used for flushing in public buildings, the usage of storm- and rainwater for washing is more heavily restricted, with it not being allowed in places such as schools, universities, libraries and sports halls. Recycled storm- and rainwater is permitted for washing in family homes and communal washing facilities (Faldager et al. 2012).

4.1.3.4 Norway

Norway lacks a legal framework that regulates stormwater alone, instead, it is paired with other legal acts that includes provisions concerning it. These laws include, the Planning and Building Act, the Water Resources Act, the Pollution Control Act and the Water Directive. There are no provisions pertaining to the recycling of stormwater, instead, such water is to be dealt with through infiltration into the ground as per the Water Resources Act. As such, when pertaining to construction projects, it should be handled in such a way that the ability for the stormwater to drain away is not inhibited by the construction project (Norwegian Ministry of Environment and Climate 2013).

As of the 1st of January 2024, new provisions in the Planning and Building Act in §28-10, resulting in changes to TEK17 §15-8 and SAK §5-4, have come into force. The provisions outline the basis of Norwegian stormwater management, which consists of a three-step solution. Smaller flows are to be managed through infiltration, moderate flows are to be delayed, and large flows safely diverted. Stormwater should be handled locally and not be fed into traditional drainage and sewage systems if possible, to avoid overloading them, and management solutions should be dimensioned for 100-year rainfall events (Norwegian Directorate for Building Quality 2024).

4.2 Interviews

Brief overviews of the various components of the systems that were interviewed are outlined in Table 9, Table 10 and Table 11, with more details given in Appendix A. A complete list of all systems can be seen under chapter 2.5 in Table 4. Rainwater was the most common type of water used, with the larger-scale projects alone drawing on storm- and rainwater.

Denmark:

Table 9. Description of the various components of the systems for which interviews were conducted in Denmark.

Projects \ Components	Borupgaard Gymnasium	Nye	Holbæk Laundry Facility	Ramboll
End use	Flushing (WC)	Flushing (WC) and laundry	Laundry	Flushing (WC)
Collection	Rooftop collection	Collection from rooftops, roads and topsoil	Collection from rooftops (with plans to collect urban runoff)	Rooftop collection
Storage	In-building storage tanks	Outdoor storage ponds	In-building storage tanks	Underground storage tank
Treatment	Filtration	Sandfiltration, pressurefiltration, ultrafiltration, UV-treatment	Filtration, chemical treatment, UV-treatment	Straining
Distribution	Separate distribution network.	Separate and purple-coloured distribution network.	Separate distribution network.	Separate distribution network.
Type of water	Rainwater	Storm- and rainwater	Storm- and rainwater	Rainwater

Sweden:

Table 10. Description of the various components of the systems for which interviews were conducted in Sweden.

Projects \ Components	Celsiushuset	LBVA	Sergelhusen

End use	Flushing (WC)	Flushing (WC)	Flushing (WC) and irrigation of green areas
Collection	Rooftop collection	Rooftop collection	Rooftop collection
Storage	Underground storage tank	In-building storage tanks	In-building storage tanks
Treatment	Straining, sedimentation, sandfiltration and UV-treatment	Straining	Filtration (Glass, salt (turbidex), anion, ultra and activated carbon)
Distribution	Separate and marked distribution network	Separate distribution network	Separate distribution network
Type of water	Rainwater	Rainwater	Rainwater

Norway:

Table 11. Description of the various components of the systems for which interviews were conducted in Norway.

Projects \ Components	Sogn Hagelab	Wikholm
End use	Irrigation of green areas	Flushing (WC), irrigation of green areas and cleaning of streets
Collection	Rooftop collection	Rooftop collection
Storage	Above-ground storage tanks	Above-ground storage tanks
Treatment	Filtration	Filtration
Distribution	Separate distribution network	Separate distribution network
Type of water	Rainwater	Rainwater

4.2.1 Interview Summaries

Summaries of the interviews conducted with the owners and stakeholders of the project were made to make the results of the interview more accessible to the reader, as well as with due consideration to potentially sensitive information in the transcripts of the interviews. Schematics for the various systems, as understood by the information provided, were created and shown in Figures 7 to 14.

Celsiushuset:

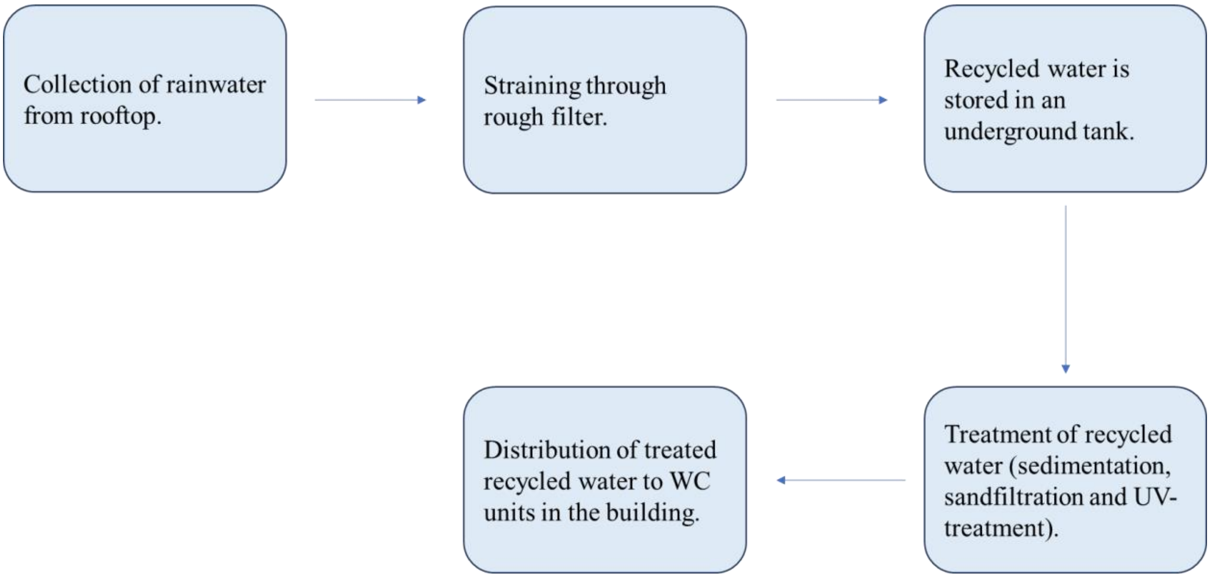

Figure 7. Schematic illustrating the flow of water for the system at Celsiushuset.

Interviewee: Project Manager at Vasakronan

Built as part of the company's internal goals for innovation and to accommodate a desired sustainability certification for the office building, the system has functioned smoothly and as intended. Roughly 60% of the water normally used for flushing has been replaced, and the recycling system has been successfully integrated together with solar panels, the solar panels share the collection area with the system and the electricity produced is used to run the system. The interviewee stated that unlike when green roofs are used for collection, the quality of the water is perceived as high. Overall, there is contentment with and the system is perceived as a fundamentally simple and effective solution. The chief issue as such is simply the climate, as rainwater is not supplied during the winter when snow covers the rooftop.

The local municipality was somewhat sceptical owing to the fact that they would be delivered the same quantity of wastewater, but able to sell less tapwater to cover their costs. The interviewee did make the case however that it was a realisation that they did not have to expand their drinking water distribution network. The cost savings arising from this meant that the municipality became more positive towards the project after that.

Sergelhusen:

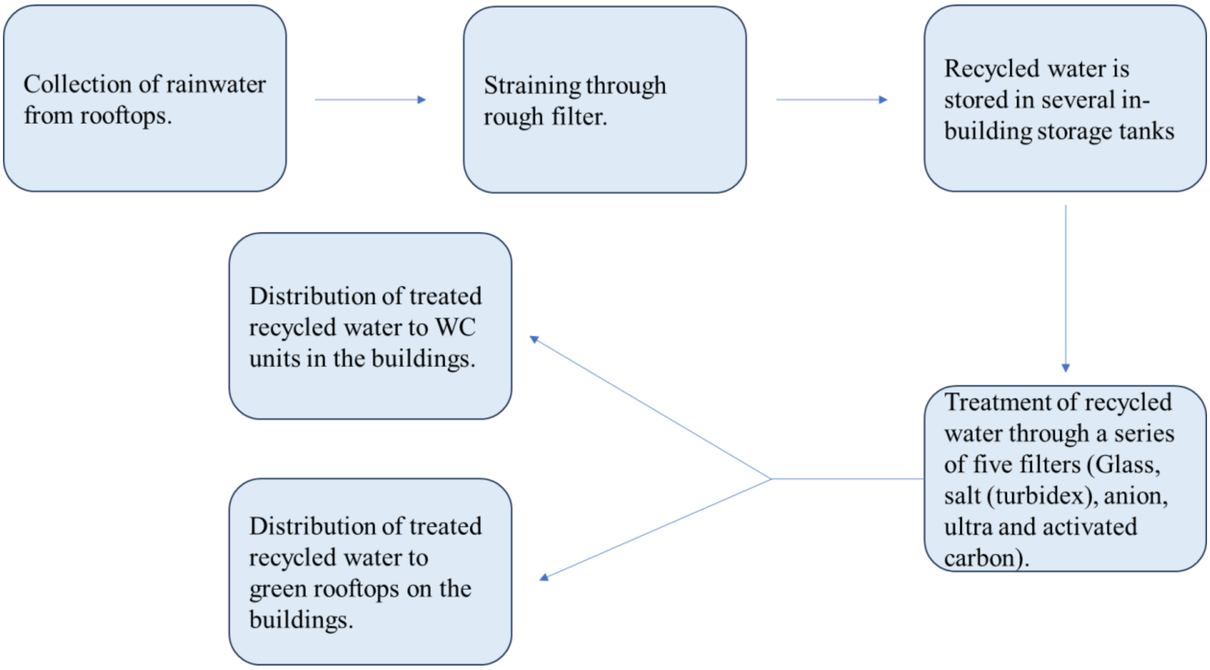

Figure 8. Schematic illustrating the flow of water for the system at Sergelhusen.

Interviewee: Chief Technician at Sergelhusen (Vasakronan)

Although there was no clearly defined ambition with the project beyond an interest in innovation and seeing whether or not they could make it work, the water recycling system at Sergelhusen did encounter some difficulties. A combination of green rooftops and the collection of the rainwater led to colouration and particles being swept along, clogging filters, and giving the recycled water a yellow appearance. This in turn necessitated the renovation and installation of activated carbon filters not initially accounted for. The stakeholders of the system do feel as though the project has considerable potential in providing water at low levels of maintenance when the initial issues have been fully resolved, as the system is considered to be simplistic in its overarching design by the interviewed stakeholder. It does not function in winter, however, as snow inhibits collection of water.

After the carbon filters were installed, the water quality improved and despite the initial troubles, the project owners are inclined to invest further in storm- and rainwater recycling. There was no overt opposition from the municipality, though the stakeholder of the system at Sergelhusen had heard from a second-hand source that there had been some reservations by the municipality. As far as the interviewee knew, this was due to how their system meant that Vasakronan would not pay for the drinking water they managed to replace, but the wastewater still was to be treated by the municipality.

Laholmsbukten VA (LBVA):

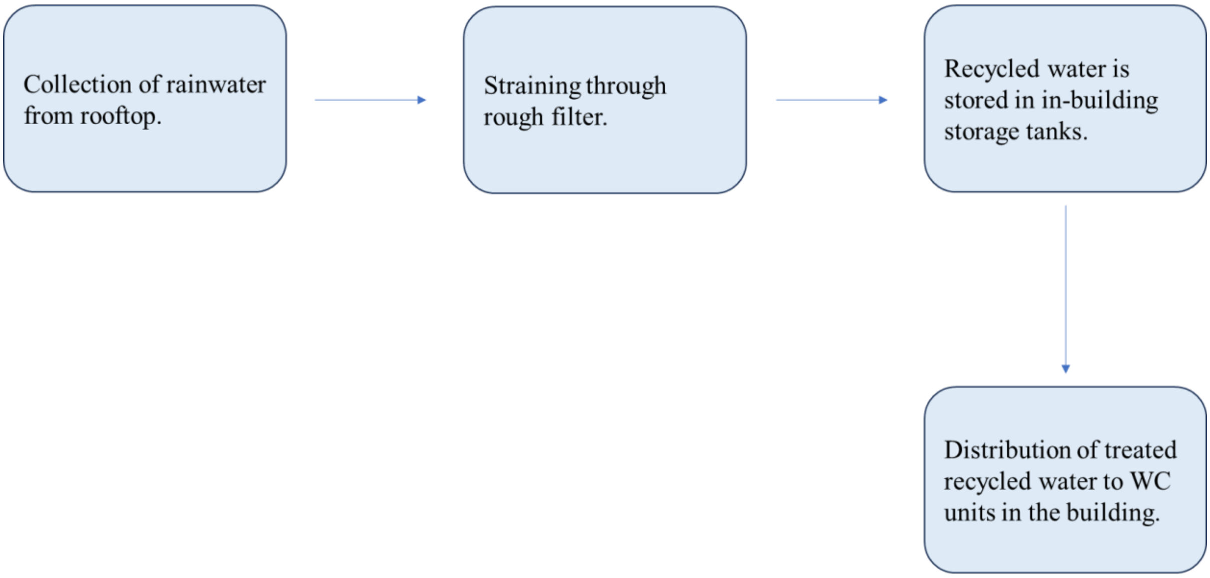

Figure 9. Schematic illustrating the flow of water for the system at LBVA.

Interviewee: Strategic Developer at LBVA

Originally conceived out of directives from the municipality, where the municipality wished to work more towards circularity and resource-effectiveness, and partially as a result of local water shortages, the system has been in operation for four years now. LBVA is largely content with the recycling, and it has operated smoothly, though they concluded that the storage tanks had been underdimensioned. The ambition was to allow rainwater to supply 80% of the water they needed for flushing, in operation though it could only supply 40%, owing to that there was insufficient capacity to store water for dry periods.

Another inhibiting factor was the prevalence of ice and snow, as the system does not function under these conditions, furthermore, there was some difficulty during the project phase of the recycling system. This contributed to a higher investment cost than was initially projected.. The new thinking required for the novel system posed some challenges in communication with contractors, but the operative phase of the system has proceeded well. The quality of the water is perceived as high.

The interviewee did remark that there is not much economic incentive for water utility companies to install these systems in Sweden, as they cannot sell tapwater to those customers. Furthermore, something they have come to realise is that novel systems can pose difficulties when ownership of the building changes, and the new owner is not as informed.

Wikholm:

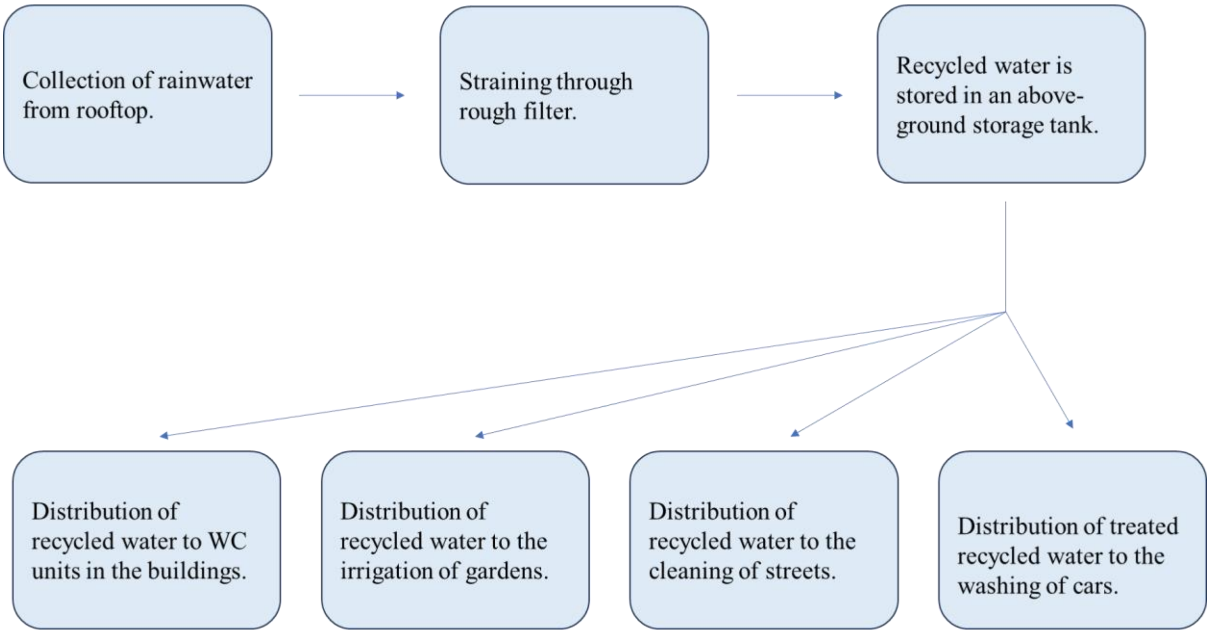

Figure 10. Schematic illustrating the flow of water for the system at Wikholm.

Interviewee: Project and Calculation Manager at Wikholm

Stakeholders from Wikholm reported in their interview that their rainwater recycling system functioned as intended and had lived up to their ambitions of adding more circularity into their value chains. It was also viewed as an important experiment to gain better understanding and experience with such systems. With Norway facing considerable challenges from stormwater, the interviewee professed that Wikholm had a desire to be involved with tackling these challenges. Another point that the interviewee raised was that recycled water would not burden the drainage in the streets, as it would have done if merely diverted as stormwater. It has operated without issue or interruptions since 2016, with the sole exception of a brief period during a drought in the summer of 2019.

The recycled rainwater is used for all the intended end-uses and has not needed to be complemented by drinking water from the local utility company, with the exception of the drought in 2019. When asked whether there was anything they would have done differently, the interviewee remarked that there was nothing they would have changed, instead being very pleased with how the project had worked in practice.

Sogn Hagelab:

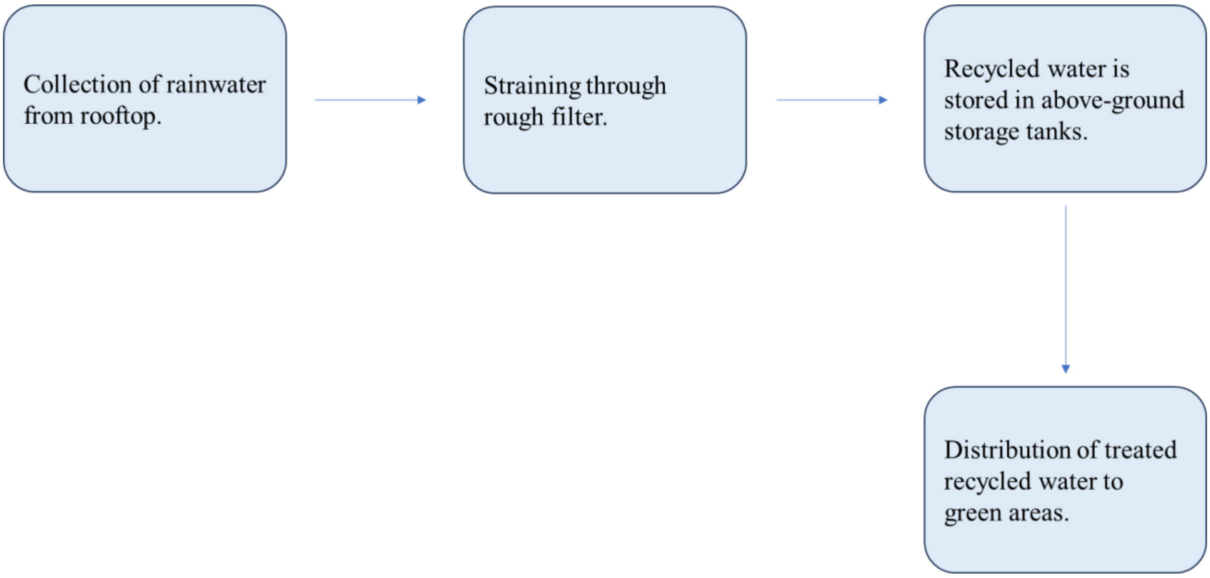

Figure 11. Schematic illustrating the flow of water for the system at Sogn Hagelab.

Interviewee: Senior Researcher at NIVA

Sogn Hagelab's rainwater recycling system was designed as a learning and demonstration area with a number of blue-green water solutions, with a reconstructed wetland, rain garden and green rooftops. There was interest from local actors and they themselves desired to conduct a small-scale test as to the viability of these solutions. Given the adverse conditions Norway is exposed to from heavy rainfall events, the interviewee considers it very important to work with water as a resource and to prevent harm to urban infrastructure.

NIVA did not set any real targets, beyond dimensioning it for a five-year rainfall event, but found that recreation could be combined with rainwater management. Funding proved to be a constraint, as did the presence of clay soil, which proved somewhat inadequate to cope with very heavy rainfall. Overall, they found their system to be fairly low maintenance, the trick was during the project phase to get green roofs into the proper shape with sloping rooftops. Furthermore, it was also a difficulty to ensure that various solutions interacted with each other. For instance, if the rain garden overflows, the intent was for the water to run into a green ditch. Transition zones can be vulnerable if the structures are subtle, and locals do not understand what they are for.

With novel solutions, communication with stakeholders was also stressed to be important so that they understood how the system functioned and was designed. There was perceived to be a lot of competence and interest towards circular storm- and rainwater solutions at the municipal level, but less so at higher political levels.

Borupgaard Gymnasium

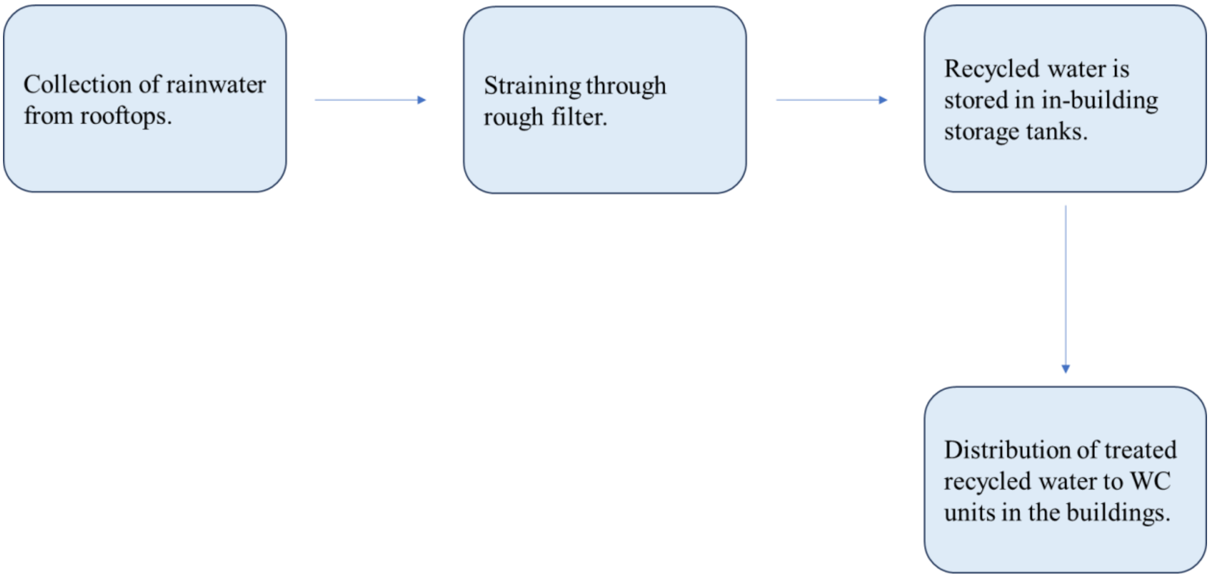

Figure 12. Schematic illustrating the flow of water for the system at Borupgaard Gymnasium.

Interviewee: Technical Service Assistant at Borupgaard Gymnasium

The rainwater recycling system at Borupgaard Gymnasium was originally created out of a desire from the principal to have the school become more sustainable, supplying water to the toilets of the entire school of some 1200 pupils and 150 teachers. The system was installed in increments to cover three buildings in total, and there were no concrete targets. Rather, they merely wished to see whether or not the system functioned.

Overall, the project has worked well and without any issues, and they have integrated it with solar panels where the water is collected from. This combination has resulted in that the system is used in the education of the pupils concerning sustainability, and something that was mentioned in the interview was also a contentment with the filter they installed. It cleans itself at intervals by backflushing, resulting in no delay to the water system that has been noticed by users.

Although there could be slight discoloration in dry times, when the ensuing first flush sweeps more particles along with it, the quality of the water is in general deemed to be high. They have informed their pupils about how the system functions and have not encountered any opposition to it.

Nye City
:

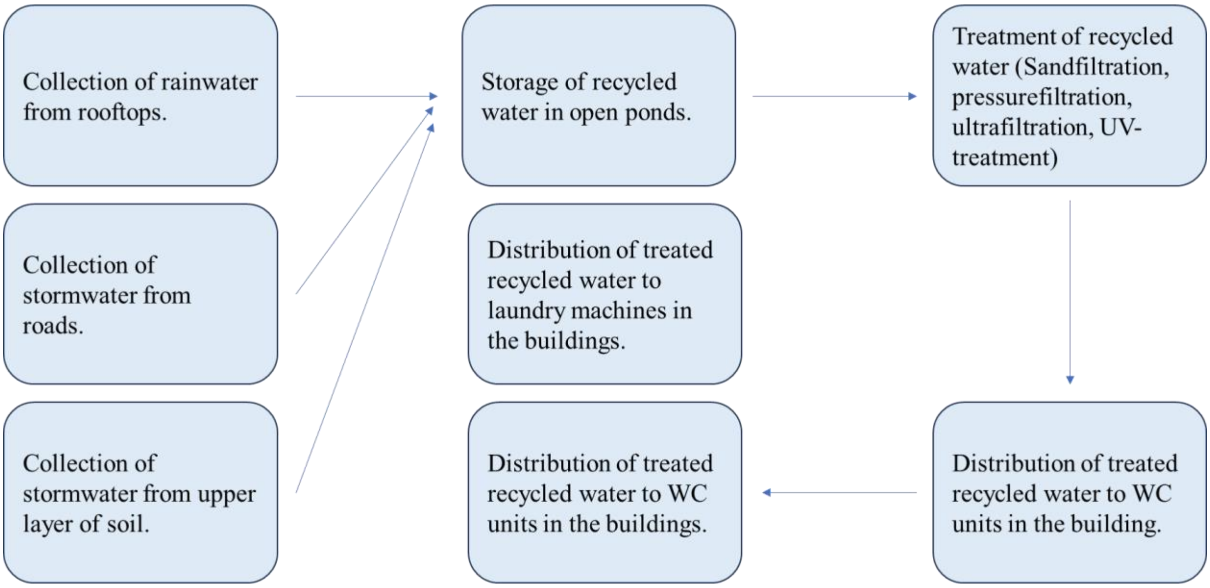

Figure 13. Schematic illustrating the flow of water for the system at Nye.

Interviewee: Project Manager at LBVA

The project at Nye is still being expanded, but now supplies water for flushing to some 200 households and as such making it one of the larger projects that have been examined. The local water utility company is, despite some issues, very content with the project and considers that it has fulfilled the ambitions they set out for it, by showing that water recycling systems can be implemented at scale in new residential areas. Furthermore, the open storage ponds help to promote recreation.

In Danish law it is permitted to use water from rooftops, however Nye was forced to seek a permit to use stormwater drainage from roads in order to construct the system. The interviewee explained that some difficulties with the system in Denmark arose from the fact that they are not accustomed to making use of alternative sources of water other than groundwater. In Sweden and Norway, it is more prevalent to use surface water instead of groundwater. This posed some challenges in the design of the water treatment system, where particles clogged the ultrafilters that needed to be diverted and replaced with regular drinking water when turbidity was too high for the UV-treatment to function.

The necessary backwashing of the ultrafilters results in the loss of some 20% of the produced water, and the high turbidity preventing UV-treatment means that only half the water that leaves the treatment facility is recycled water. This could have been mitigated by having the inlets to the open storage ponds further away from the intake of the water to the treatment facility. That would have ensured that particles had more time to sediment. Another lesson that has been drawn from the project is that a large storage will enable a greater buffer capacity in times of drought.

Based on feedback from the users, the water quality is considered to be high, and the only issues have been with slight colouration brought by fine particles. The users are aware that it is recycled storm- and rainwater and have no issues with the colour.

The interviewee reported a high level of engagement from the involved actors, the water utility company, the real estate developer and the municipality. That said, a barrier is that it is not a good case on solely economic grounds. Especially as these systems are new and this lack of habit contributes to higher costs for the producers. Furthermore, the ca se for these systems were better for new areas where consumers did not have to pay additional fees for renovation.

Ramboll:

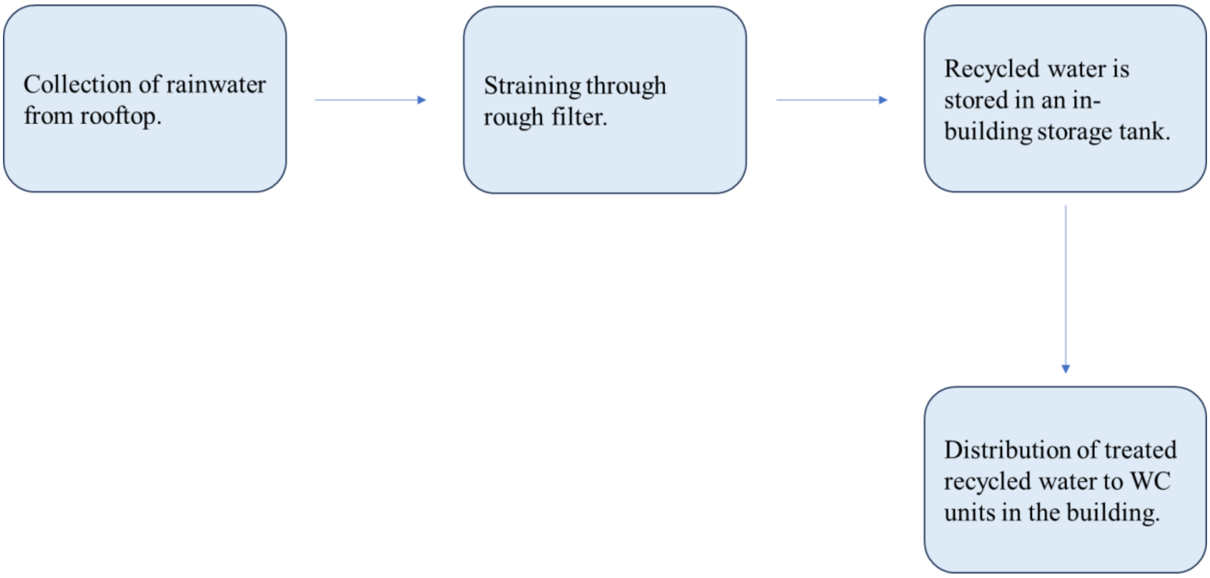

Figure 14. Schematic illustrating the flow of water for the system at Ramboll.

Interviewee: Senior HVAC Engineer

Originally conceived in 2008, the rainwater recycling system at Ramboll was installed in a bid to make the building more sustainable. This was motivated in part by the pressure on the diminishing groundwater reserves in Denmark, as well as a hope they might save money. Implemented and in operation almost continuously since 2010, the water recycling system at Ramboll's headquarters is deemed by the company to have been a successful endeavour. Furthermore, a benefit that they perceived was that there is less lime in the rainwater, meaning less buildup in the toilets.

There have been very few issues, the only maintenance that has been required was the occasional cleaning of the storage tank every few years. Some alterations had to be made however, as the system was tailor-made, because dirt and grime was brought into the system as first flush after dry periods. This necessitated that the pipes in the distribution systems had to be redesigned to allow for back-flushing to clean them. The quality of the water was described as very high, only occasionally was there some small particles in it.

Some important conclusions besides the flushing of the pipe network that they drew, was the benefit of having a sloping storage tank, as it allowed easier cleaning. The dirt simply accumulates in the lowest point in the storage tank. Furthermore, the interviewee stressed that the local cost of water was important as far as these systems were concerned, which in turn will impact what value you get from the system. There is still the need to pay for the treatment of wastewater and that will depend on the local utility. In Copenhagen, those using storm- and rainwater recycling systems only had to pay half price for the treatment of wastewater. Though this was not the case everywhere.

The interviewee considered that it was fairly important to work with the recycling of storm- and rainwater, but that it was not worth it for smaller buildings. Installations in places such as Ramboll are more convenient owing to larger collection surfaces and staff that can maintain the water systems.

Holbaek Laundry Facility:

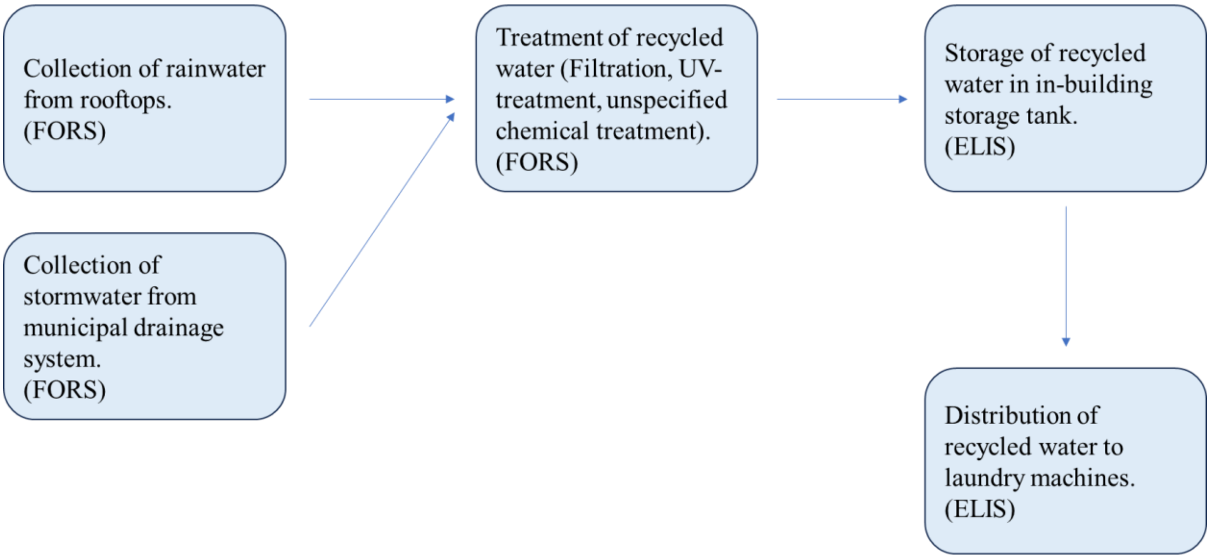

Figure 15. Schematic illustrating the flow of water for the system at Holbaek.

Interviewees: General Manager at Elis, Project Developer at FORS A/S, Civil Engineer and Owner of BOVAK.

Still in the trial phase, the project is not yet in operation. There are multiple actors involved, with Elis operating the laundry facility, FORS A/S supplying the water, and BOVAK having contributed to designing the system.

The project came about out of a desire to use less drinking water for the laundry operation at Elis, as such becoming more sustainable. It has both been tested for rainwater collected from rooftops, but they are also doing tests for using the water from the traditional drainage systems. Meanwhile, FORS also had a desire to work with more innovative solutions that centred around a desire to stop wasting water owing to strain on groundwater resources. A goal they have, as per the interviewee from FORS, is to stop wasting drinking water where it was not needed (for non-potable purposes), seeking to cut down on their use of groundwater at about 1% a year.

Water from rooftops has been perceived as being of high quality, however the stormwater more broadly could vary in quality significantly, especially during the first flush after dry periods. To remedy this, the plan is to employ modular filtration systems. A hope with the system was that the alternative water would be softer than groundwater, and it proved to be, albeit not as soft as they had hoped. Something that the interviewee at FORS noted as a challenge was that the incoming recycled water had a variable quality, prone to changing over time moreso than groundwater.

Something that has been noted in FORS, as far as the quality of the water goes, is to establish more clarity as to the quality of the recycled water that they provide to customers. There has been interest from industries more so than politicians, but the interviewee has perceived a need to streamline and make it easier for customers both to install storm- and rainwater recycling systems, or to purchase recycled water. A system under consideration was establishing classes of recycled water, such as A, B and C, where all would have different degrees of treatment.

Funding was received for the projects from the government agencies, namely the board of water utility companies, however a problem that was reported was to ensure that politicians understood the system and how it would function in practice. With novel technical solutions being perceived as difficult to communicate with policy-makers due to a lack of understanding of how new systems function.

4.2.2 Parameters

In Table 12, the raw data acquired during the interviews are presented. Some of these were calculated based on other data provided as a result of the interviews and presented in 3.3.2. In Table 13, the functional units converted from the raw data are presented in turn.

The different treatment steps, only the quantity of steps for each system being presented in Table 12, are detailed under 4.2 and Appendix A.

The difference between availability and the share of water replaced for the intended end-use is that the system could be in operation at all times, but it might not necessarily mean that it was either meant to or is able to replace all the water for the intended end-use. To use a theoretical example, if water is continually available from collection or storage, the availability would be 100%. If the stakeholder elects not to use some of the water that comes from collection, or simply dimensioned the system to only replace some water for the intended end-use, then the share of water replaced for intended end-use will be less than 100%.

If a system was designed to, when it is in operation, replace all the water for the intended end-use then the availability is equal to the share of water replaced for the intended end-use. At Nye, for instance, the system produces water at all times, but owing to the turbidity some half of it cannot be used. As a consequence, the availability is 100%, but the share of water for intended end-use is only 50%. The total, when it was given, merely denotes how large a percentage of the total water consumption the system provides, factoring in other end-uses besides the one the system was supplying water for.

Table 12. Data acquired directly and calculated through the interviews.

Parameters: \ Projects:	Celsius-huset	Sergel-husen	Borupgaard Gymnasium	LBVA	Wikholm	Nye	Ramboll	Holbaek (Est.)
Energy use [kWh/year]	70-100	-	-	~20 (Estimate)	Negligible	~2300-3300	~4300-5000	-
Water recycled [m^3/year]	~940	-	631	100	208 (Potential of ~1260)	~6500-7300	~2400-2800	~5000 (32 000 planned)
Operating costs [EUR/year]	≥7.2−10.8	4500	-	≥ ~2.2	~700	~21670	~1300	~4700 (Elis)
Investment cost [EUR] (Adjusted for inflation*)	~30000 36000*	260000-350000 320000-430000*	-	44-54000 53-65000*	~21000 27000*	~3350000 4000000*	~130000 175000*	~87000 (Elis)
Availability [%]	60	>60	89	40	100	100	99	99 (In trial)
Share of water replaced for intended end-use [%]	60	-	89	40	100	~50 (40 of total)	60-65 (20-35 of total)	100 (In theory as per trial)
Time in operation [years]	4	3	4	3.5	8	3	14	0
Intended lifespan of project [years]	50 (20 for moving parts)	20	20-25	15	50	50	50	20
Number of water treatment steps	4	5	1	1	1	4	2	4+
Dimension of storage [m^3]	72	110	57	8	10	6200	150	160

In Table 13, the data was converted into functional units, largely per cubic metre of recycled water, to then serve as a basis for the MCA.

Table 13. Table of the data converted into functional units, for comparison in the MCA.

Functional Units: \ Projects:	Celsius-huset	Sergelhusen	Borupgaard-Gymnasium	LBVA	Wikholm	Nye	Ramboll	Holbæk (Trial)
Energy intensity [kWh/m^3]	0.07-0.11	-	-	~0.2	Negligible	0.35-0.45	1.8	-
Carbon emission intensity [gCO_2/m^3]	1.6-2.5	-	-	~8.2	Negligible	51-66	277	-
Cost of water [EUR/m^3]	0.011-0.015	-	-	~0.022	3.4	3.0-3.3	0.46-0.54	~1.1
Investment cost per cubic metre over intended lifespan [EUR/m^3]	0.76	-	-	35.3-43.3	2.6	11.0-12.3	1.25-1.5	0.87 (For Elis, at trial-phase level) 0.13 (For Elis, in theory as per plans)
Availability [%]	60	>60	89	40	100	100	99	99

4.3 Multi-criteria analysis (MCA)

Described in Table 14 are the spans that were used to assign the values on the 1-5 scale for the multi-criteria analysis, with lower values indicating a better performance.

Table 14. The various spans for which values are assigned during the MCA.

Functional Units: \ Values	1	2	3	4	5
Energy intensity [kWh/m^3]	<0.19	0.2-0.39	0.4-0.9	0.91-2	>2
Carbon emission intensity [gCO_2/m^3]	<5	5-9.9	10-50	50-100	>100
Cost of recycled water [EUR/m^3]	<0.05	0.05-3.99	4-8	8.1-20	>20
Investment cost per cubic metre over intended lifespan [EUR/m^3]	<0.5	0.5-0.99	1-4	4-20	>20
Availability [%]	100	99-90	89-50	49-30	<30

4.3.1 Final evaluation (Chart)

The data, converted into functional units, was assigned values in accordance with Table 14, which in turn was summarised in Table 15. Tables illustrating the weighted values can be found in Appendix D.

Table 15. The systems when assigned values for each parameter in accordance with Table 14, without weighting. The lower the score, the better the system performed.

Functional Units: \ Projects:	Celsius-huset	LBVA	Nye	Ramboll	Wikholm
Energy intensity [kWh/m^3]	1	2	2-3	4	1
Carbon emission intensity [gCO_2/m^3]	1	2	4	5	1
Cost of water [EUR/m^3]	1	1	2	2	2
Investment cost per cubic metre over intended lifespan [EUR/m^3]	2	5	4	3	3
Availability [%]	3	4	1	1	1

The same result as in Table 15 was illustrated in Figure 16. Illustrated in the spider chart is that those systems enclosed by the green pentagon representing the 'Average System' are the systems that are quantitatively more sustainable than the 'Average System'.

Broadly, the systems performed similarly to the theoretical 'Average System'. They performed best in the operative aspects, with investment costs excluded, though they were generally closer to the 'Average System' for the investment costs. Danish systems are disadvantaged by their carbon emission intensity, relative to Swedish and Norwegian systems.

That investment costs can be a hindrance is illustrated, as it was generally the weak point where the systems in aggregate performed worst. Celsiushuset did however manage to overperform the others, and provides an example that storm- and rainwater recycling systems do not have to have higher investment costs than traditional drinking water systems.

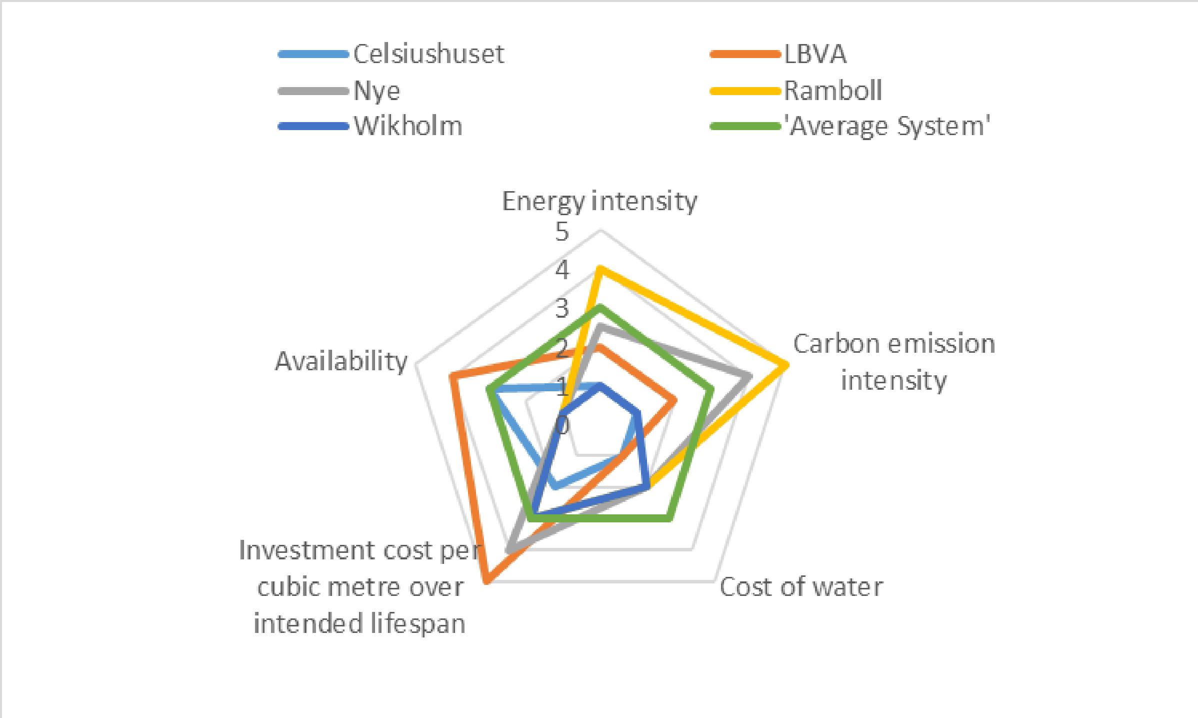

Figure 16. Spider chart illustrating the performance of the systems relative to each other and an ‘Average System’ that acts as a benchmark, without weighting.

Using the results in Table 15, weighted and non-weighted total sums were compiled in Table 16 to provide an overview of the relative performance of systems.

Table 16. Table illustrating the performance of the systems relative to each other and an ‘Average System’ that acts as a benchmark, with and without weighting. The lower the score, the better the system performed.

Projects	With weighting	No weighting
Celsiushuset	8.6	8
LBVA	16.4	14
Nye	13.6-14.5	13-14
Ramboll	14.1	15
Wikholm	9.5	8
‘Average’ System	15	15

4.4 Sensitivity Analysis

Original spans, without weighting:

Absent weighting, with all criteria being equal, the systems overall perform better. This is largely due to the fact that the investment costs count for less out of the total sum.

Celsiushuset and Wikholm both still perform strongly regardless of weighting. LBVA benefits from the lower emphasis on investment cost without weighting, whereas Ramboll's high energy intensity and the electricity mix in its region disadvantages it, owing to the high carbon emission intensity.

Overall, only Celsiushuset and Wikholm hold a noteworthy difference compared to the 'Average System'. The general trend however tilts towards a better performance relative to the 'Average System', as opposed to a worse one. Indicating a tendency towards the recycled storm- and rainwater being quantitatively more sustainable.

Alternative spans:

As part of the sensitivity analysis, alternative spans chiefly found in literature, with the exception of for availability, were chosen to constitute the average value of 3. The alternative spans chosen were the following:

Energy intensity: For the energy intensity, 3 encompasses the span enveloped by the energy intensity of the production of drinking water in China, the US, Denmark and Sweden presented in Chapter 4.2. 0.29 [kWh/m^3] in China constituting a lower limit, with 1.38 [kWh/m^3] in Sweden constituting the upper limit.

Carbon emission intensity: The carbon emission intensity was given the rating of 3 for those that fell between 13 gCO_2/m^3 (Sydvatten's carbon emission intensity calculated for the regional electricity grid) and 165 gCO_2/m^3 (the European average).

Cost of water: For the cost of water, the rating 3 was set as to encompass the Swedish, Norwegian and Danish cost of drinking water (with 3.8 EUR/m^3 for Swedish apartments constituting a lower limit, and 9.85 EUR/m^3 for Danish water setting the upper limit).

Investment cost per cubic metre over intended lifespan: The upper and lower bound of the rating 3 was here set to constitute the estimated upper and lower limit of investment costs per cubic metre for traditional drinking water systems, between 1 and 9 EUR/m^3.

For availability, the spans were made stricter as to provide a better comparison with the availability of drinking water, which was assumed to have a near-constant availability. The average value of 3 was selected as needing an availability of 80-94.9%. This was to allow some shortfall from 100% owing to the intermittent storm- and rainwater supply.

In Table 17, the alternative spans are detailed.

Table 17. The various alternative spans for which values were assigned for the sensitivity analysis.

Functional Units: \ Values	1	2	3	4	5
Energy intensity [kWh/m^3]	<0.19	0.2-0.29	0.29-1.38	1.39-2	>2
Carbon emission intensity [gCO_2/m^3]	<5	5-9.9	13-165	166-200	>200
Cost of water [EUR/m^3]	<0.05	0.05-3.79	3.8-9.85	9.86-15	>15
Investment cost per cubic metre over intended lifespan [EUR/m^3]	<0.1	0.1-0.46	0.47-4.16	4.19-20	>20
Availability [%]	100	99-95	94.9-80	79.9-60	<60

Using the alternative spans in Table 17, values were assigned for the systems as detailed in Table 18.

Table 18. The systems when assigned values for each parameter in accordance with Table 17, without weighting. The lower the score, the better the system performed.

Functional Units: \ Projects:	Celsius-huset	LBVA	Nye	Ramboll	Wikholm
Energy intensity [kWh/m^3]	1	2	3	4	1
Carbon emission intensity [gCO_2/m^3]	1	2	4	5	1
Cost of water [EUR/m^3]	1	1	2	2	2
Investment cost per cubic metre over intended lifespan [EUR/m^3]	3	5	4	3	3
Availability [%]	4	5	1	2	1

Overall, the systems perform strongly in operative aspects even with the alternative spans. Danish systems do suffer as before from far more significant carbon emissions than the Swedish or Norwegian systems, as the Danish regional grid relies on more fossil fuels. Some parameters are nudged into the average span for those systems that teetered on the edge in the first iteration of the multi-criteria analysis.

Investment costs remain a weak point overall, at best, the storm- and rainwater recycling systems fall within the average value. With more stringent availability, Celsiushuset and LBVA are both disadvantaged.

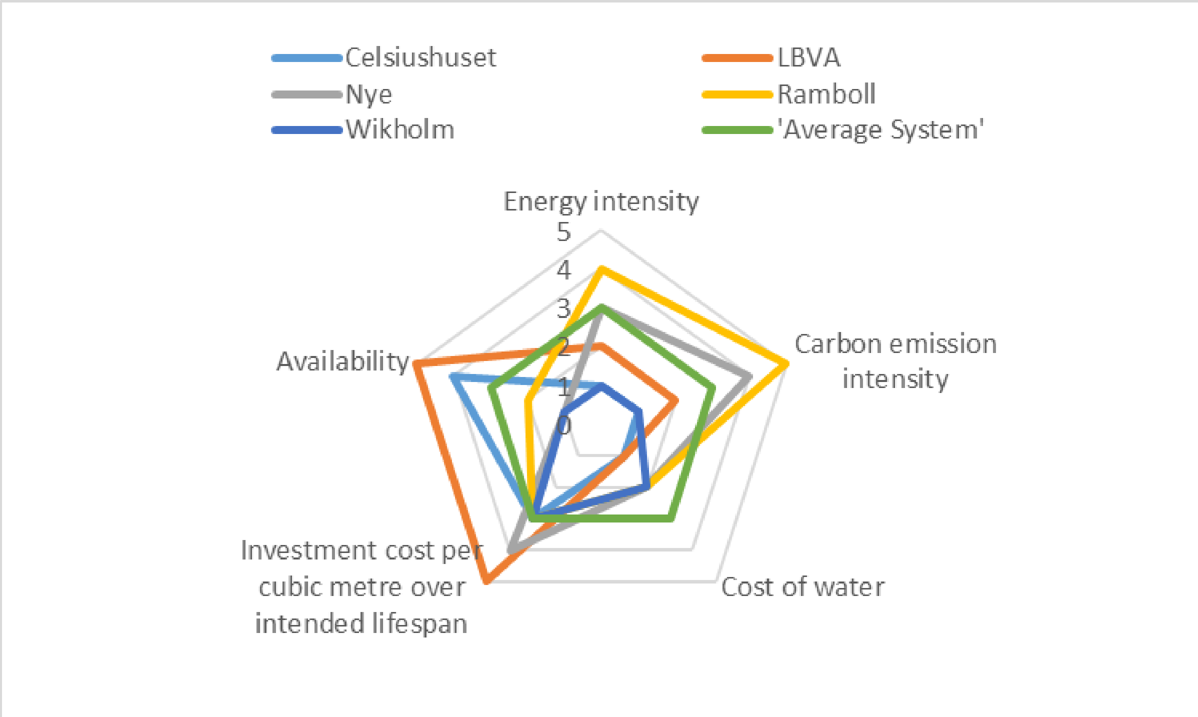

Figure 17. Spider chart illustrating the performance of the systems relative to each other and an ‘Average System’ that acts as a benchmark, using alternative spans to assign values, without weighting.

Alternative spans:

The alternative spans, as illustrated in Table 17, generally pushes the systems closer towards the ‘Average System’, the wider spans making it more difficult to over- or underperform the benchmark. Overall, this comparison disadvantages the systems slightly, as some performed better than traditional drinking water on several parameters, albeit not by large margins.

Using the alternative spans in Table 18, weighted and non-weighted total sums were compiled in Table 18 to provide an overview of relative performance.

Table 18. Table illustrating the performance of the systems relative to each other and an ‘Average System’ that acts as a benchmark, with alternative spans used to assign values, both with and without weighting. The lower the score, the better the system performed.

Projects	With weighting	No weighting
Celsiushuset	11.4	9
LBVA	17.3	15
Nye	14.5	14
Ramboll	15	15
Wikholm	9.5	8
‘Average System’	15	15

5. Discussion

The aim behind this study was to examine the state of storm- and rainwater recycling in Scandinavia and attempt to evaluate the sustainability. Both whether or not storm- and rainwater recycling could demonstrably be a sustainable source of alternative water relative to the traditional drinking water systems, as well as what technological solutions for storm- and rainwater recycling systems appear to have been more sustainable than others. To this end, it was also important to hear from stakeholders directly and learn from their experiences, to find out whether or not the systems functioned as intended.

As the recycling of storm- and rainwater is a fairly nascent phenomenon in Scandinavia, it is perhaps not surprising that there still is much to learn, as well as necessary clarification as far as regulation goes. Based on the results of the interviews, those who had carried out such projects reported a high level of engagement, with a desire for sustainability being the most important driver, and expressed contentment with the systems. The interviewees also considered storm- and rainwater recycling to be an important solution to various challenges, though the challenges varied somewhat depending on the region the interviewee was in. Overall, the methods employed in this study worked well relative to the research questions that the study set out to answer, though data collection was a challenge. With fewer complete sets of quantitative data and systems interviewed than would have been ideal to lend more weight to the results.

Literature study:

What the literature study mainly set out to try and answer was whether or not storm- and rainwater recycling as a concept could be sustainable in Scandinavia. Because the topic itself is so broad, it was important not only to understand what components storm- and rainwater recycling systems have, but also gauge the state of storm- and rainwater recycling both in Scandinavia and internationally. Furthermore, the local conditions that storm- and rainwater recycling face in Scandinavia also needed to be established.

Given the composition of water use in Scandinavian countries, and studies such as Mikkelsen et al. (1999) and Villareal et al. (2005), the literature study confirmed that storm- and rainwater recycling systems can be used to make significant contributions to the water supply in Scandinavia. For instance, if drinking water was replaced by recycled storm- and rainwater for the uses of flushing and the washing of clothes, it would decrease the annual water consumption of drinking water by several percent based on the water consumption profiles of the Scandinavian countries found in the literature study. If one looks beyond household use and factors in uses such as flushing at workplaces as well as water for industrial production not requiring potable water, the fraction of drinking water that could be replaced by recycled water would increase further. Although cost-efficiency and other practical considerations may not make it suitable for deployment everywhere, it still has potential for large-scale deployment.

The literature provided support for the assertion that storm- and rainwater recycling could be deployed at scale. Thereby helping to secure alternative water, contribute to flood management, and combat water shortages (Hatt et al. 2006). There is already large-scale deployment of storm- and rainwater recycling in many other European countries, such as Germany and the United Kingdom (Campisano et al. 2017). Furthermore, though no study that evaluated the performance of storm- and rainwater recycling systems in Scandinavia has been performed before, such a study in the United Kingdom found that storm- and rainwater recycling systems can be a net benefit when deployed at scale. That study asserted that storm- and rainwater recycling can provide very cheap water for non-potable purposes, and contribute to savings in costs, energy consumption and carbon emissions relative to drinking water. It also concluded that whether or not the storm- and rainwater recycling system is a net benefit depends on factors such as how the system is designed and local conditions, e.g. rainfall (Fredenham et al. 2020).

Some benefits of the recycling of storm- and rainwater can be difficult to quantify, such as in regard to the context of global instability and supply chains. In a scenario where chemicals necessary for the traditional water treatment plants become scarcer, this could put significant pressure on the costs of drinking water. Having phased out the use of tapwater for places where it is not needed could as such help to shore up a reliable supply of water. In the event of shortages, there would be less demand if activities not requiring potable water already operated with alternative water, rather than tapwater.

A difference between Scandinavian and some countries where storm- and rainwater recycling was common, is the lack of government support or even acknowledgement of the practice. Storm- and rainwater recycling in Scandinavia would benefit from clearer regulations, especially Sweden and Norway, as the lack thereof creates some uncertainty for those wishing to install such systems. The absence of any national strategies and targets may also hamper efforts to have storm- and rainwater recycling systems deployed at scale, though as there have been recent mentions of viewing storm- and rainwater as a resource such as by the Swedish Environmental Protection Agency (2024b), that may be subject to change.

Given the cold climate, something that particularly affects the Swedish and Norwegian interior, snow is increasingly a factor that could negatively impact the overall efficiency of storm- and rainwater recycling systems the further north and inland one goes.

All Scandinavian nations have projections for the price of drinking water increasing in the future, driven in part by significant investment needs in traditional water infrastructure (Svenskt Vatten 2023b; DANVA 2023; Norsk Vann 2024). This could contribute to making recycled storm- and rainwater a more sustainable source of water relative to drinking water, as a challenge for recycled storm- and rainwater in Scandinavia is that there is fairly abundant and cheap drinking water available.

Taken together, the literature study illustrated that storm- and rainwater recycling in Scandinavia has the potential to be a sustainable source of alternative water, albeit not everywhere and necessitating considerations to both local conditions and system design. Given the prevalence in other European countries with temperate climates, there was nothing to suggest that storm- and rainwater recycling as a concept would not be sustainable in Scandinavia. Rather, that it could potentially make significant contributions to the Scandinavian water supply, especially further south.

Interviews:

The interviews yielded many insights into the practical experiences of the stakeholders involved with the storm- and rainwater recycling systems in Scandinavia and answered the third research question. This included smart design choices, things that would have been done differently and if there had been any difficulties in having the system approved by the local municipalities.

Broadly speaking, when asked about their motivations for installing the systems, the owners of the storm- and rainwater recycling systems in Denmark generally spoke more of a desire to reduce a strain on groundwater resources. Frequently citing concerns about overuse and contamination by pesticides and industrial activity. In Norway, with more frequent and heavy precipitation, the focus lay more on a desire to collect water for the dual purposes of using it as a resource, but also to help protect urban infrastructure. Motivations for storm- and rainwater recycling in Sweden varied, with the interviewees from the real estate company of Vasakronan citing a desire to make their buildings more sustainable in general, partially to help provide certifications of sustainability of their office buildings. For LBVA, local water shortages played an important factor for why their rainwater recycling system was installed. Concern for Danish groundwater resources was echoed in literature (International Water Association 2022), as was the Norwegian challenges faced by damage from stormwater (Norwegian Directorate of Building Quality 2024). In Sweden, the desire for sustainability in general was cited in the survey conducted by Holm & Schulte-Herbrüggen (2021), as was concerns of water shortages, to appear as environmental frontrunners and to safeguard freshwater resources. This aligned with the findings of this study, supporting that storm- and rainwater recycling systems can and are used to tackle several different challenges.

The chief ambition in regard to the performance of the systems that was cited, was a desire to see if the storm- and rainwater recycling systems could function, with few having set concrete targets against which performance could be measured. As such, almost all those interviewed expressed that the systems had lived up to the ambitions they had initially. The systems in operation were deemed by users to work well for larger buildings with significant rooftop space, such as office buildings and schools, with some expressing scepticism as to their viability for single-family homes.

Rainwater collected from rooftops in particular was a popular and frequently cost-effective solution, cited by stakeholders as being a fundamentally simple and sustainable method. The rainwater collected from rooftops seemingly required little in the way of treatment and was universally deemed to have high quality, with the only reported issues arising in conjunction with green roofs, or sparingly during first flush. As the water was collected on rooftops, gravity could do much of the work in transporting the water, as such reducing the amount of pumping necessary. It also had the added benefit in places such as Ramboll's Headquarters, of reducing the amount of lime in the toilets owing to the recycled water containing less of it. The combination of low or no treatment, with less pumping required, meant that some of the systems using rainwater collected from rooftops could provide water at very low costs and with negligible energy consumption, such as Celsiushuset and Wikholm.

An exception to the low energy consumption of systems using rainwater with low treatment, was Ramboll. Though it is important to note that Ramboll's system is well over a decade old, contrary to all the other systems. As noted by Fredenham et al. (2020), there have been recent innovations in more energy efficient pump design, meaning some of the higher energy consumption may be attributed to the age of the system.

The relatively consistent high quality of rainwater was in contrast to stormwater. Stormwater from roads and topsoil could pose some challenges with inconsistent quality of the water before treatment, something remarked upon by both the interviewee for Nye and for the stakeholder from FORS, when interviewed about the Laundry Facility at Holbaek. On the other hand, stormwater did allow for collection on a far larger scale than water from rooftops.

Simple design choices also proved to have a very significant impact on the production of recycled water, and as such the overall efficiency of these systems, something alluded to in other studies (Fredenham et al. 2020). For instance, having storage of a sufficient capacity proved to be critical to effectively make use of the intermittent water supply during dry periods. The need for sufficient storage was something that was also emphasised in other studies regarding storm- and rainwater recycling such as the case study of Ringdansen in Sweden (Villareal et al. 2005). At LBVA's facility, the lack of sufficient storage slashed the share of water replaced from an intended 80% to 40%. This in turn meant that the investment cost per cubic metre was twice as high than it would have been otherwise. With investment costs for the system at LBVA already higher than initially projected by the stakeholders, lower than intended production of recycled water makes it more difficult to recoup the value through recycled water.

Wikholm likewise had a smaller storage, but more abundant and frequent rainfall meant that this did not affect the performance. In Nye, the water intake to the treatment facility was too close to the inlet of their open storage ponds, resulting in 20% of the water produced being needed to flush the ultrafiltration. A further half of the water could not be used, owing to having too high a turbidity for the UV-treatment to work. The costs at Sergelhusen were influenced by a need to reconstruct parts of their system and add more treatment steps in order to remove the discolouration brought on by using water from green rooftops. The considerably more complex design and need for maintenance of their storm- and rainwater recycling system led to far higher operating costs than the likes of Celsiushuset.

The cold climate proved to be a significant hindrance, less so for reasons such as how biofilters might not function owing to the microbes not being efficient at those temperatures, and more so for the simple reason that snow prevents collection. This was not an issue in Denmark or places with more temperate climate, with rainy winters as opposed to snow covering the landscape for months on end. For those projects in Sweden especially, it did however become the single most important inhibiting factor to availability. For projects like Celsiushuset, an availability of what might have been 100% during the year otherwise, was reduced to 60% owing to the prevalence of snow cover during several months of the year. It can as such be reasoned that storm- and rainwater recycling systems in and of themselves can not replace traditional systems entirely during the winter months in colder regions. However, even despite the snow, the systems could still make very meaningful contributions and drastically slash the usage of drinking water, meaning that the climate does not negate their efficiency altogether. Furthermore, it could be argued that climate change will contribute to decreased snow cover, which could in turn benefit the availability for storm- and rainwater recycling for those systems limited by snow cover for significant periods of the year. On the other hand, longer dry periods could also affect performance, something that none of the systems reported that they had considered when dimensioning storage.

Something else that was stated to be a hindrance was the investment costs, which some of those interviewed considered to be expensive, and in some cases like LBVA had exceeded initial estimates. This was reflected in the previously mentioned survey conducted by the Montana Pollution Control Agency (2024), where investment costs for large-scale storm- and rainwater recycling systems ran up into the millions of EUR and necessitated stakeholders to secure multiple sources of funding. Some projects attributed this to that the technical solutions are fairly novel, this meant that there was a lack of know-how and experience in installations, which contributed to higher costs. There was optimism that as these systems would become more prevalent, this would be less of a barrier as costs would fall. When compared to investment costs needed for traditional systems however, the storm- and rainwater recycling systems were generally in the same range, if not cheaper. The cost was however borne by the stakeholder that installed the system, as opposed to the water utility company.

A significant point of friction and potential barrier to the build-out of storm- and rainwater recycling systems was reported to be the difficulty for water utility companies with how their services are financed. They still receive the same quantity of wastewater, even as they are unable to sell the same volumes of drinking water that they use to help fund their operations. This, coupled with grey areas and regulatory uncertainties (especially in Sweden and Norway) illustrates that policymakers have not adapted legislation to account for storm- and rainwater recycling. It was however highlighted that storm- and rainwater recycling systems can decrease the need for expensive build-out and maintenance of traditional distribution systems. It can also contribute to better water management which could lower costs on society derived from flooding and the accompanying damages on urban infrastructure. These benefits are harder to quantify in the context of individual systems, however.

Despite the issues that had been encountered, the stakeholders appeared content with the storm- and rainwater systems at large and many of them considered it both to be important to work with storm- and rainwater recycling, as well as stated being open to investing more in such systems in the future.

Several recommendations as to smart design were provided, that the stakeholders had found made it easier to operate and maintain the systems. Among these were to ensure that the pipes could be back-flushed and use sloping storage tanks. Particles then sedimented at the bottom and made the cleaning of the storage tanks easier.

An interesting aspect of some of the storm- and rainwater recycling systems was how they sometimes integrated several end-uses. Sites like Nye and Sergelhusen illustrate how it can be combined with promoting recreation and biodiversity. The importance of avoiding contamination for water that is intended as drinking water means that alternative water, intended for non-potable uses, can be used more flexibly in multi-purpose systems than drinking water.

Storm- and rainwater recycling systems can also be effectively integrated together with solar panels, such as at Borupgaard Gymnasium and Celsiushuset. This was stated in international literature (Alazzam 2024), but appears a good option for Scandinavian conditions too. The water was perceived to be clean by the users, and that means that rooftops especially could be employed for a dual use, renewable energy and providing an alternative water source. This, combined with recommendations from project owners that larger rooftops and fewer floors made for more efficient systems, means that there would in theory be significant potential for build-out of storm- and rainwater recycling systems alongside solar panel installations. For places like schools and workplaces, that also means that the usage of the storm- and rainwater recycling system coincides with the daylight hours, when the photovoltaic electricity is being produced.

Multi-criteria analysis:

The multi-criteria analysis was important in answering the first and second research question, when backed by the literature study. In the multi-criteria analysis, when held to the standards of a system utilising drinking water, with the exception of for availability, the systems largely performed well. Although the storm- and rainwater recycling systems frequently performed similarly to what one might expect from drinking water, recycling systems generally scored lower than the theoretical ‘Average System’. As the ‘Average System’ uses drinking water, albeit with the availability of recycled water, it acts as a benchmark.

With a wide range of scopes and sizes of systems, a consideration was whether or not there would be a stark contrast in performance between larger or smaller scale projects. When evaluated in the MCA however, the storm- and rainwater recycling systems proved to be sustainable on both larger and smaller scales, something also found in studies such as that by Fredenham et al. (2020). Based on the interviews, there was no significant discrepancy in contentment between the likes of the systems at Nye, or Celsiushuset. Despite the issues that Nye had with high turbidity in the water, it still managed to perform relatively well next to the ‘Average System’ in the multi-criteria analysis. Both smaller and larger scale systems also contributed to significant water savings for the intended end-uses in all the evaluated systems.

Being a rather novel solution, some of the projects proved to be more costly than initially anticipated by the stakeholders, such as LBVA and Nye. However, broadly speaking they still appear to compare well to more traditional systems. The more expensive investment costs per cubic metre of water relative to traditional drinking water systems were mitigated by a cheaper cost of water when the systems were in operation.

Investment cost and difficulty to maintain was influenced by how advanced the water treatment was, as well as design choices, something that was supported by other studies (Fredenham et al. 2020; Montana Pollution Control Agency 2024). As far as energy consumption and operating costs, some of the more simplistic systems proved to be significantly cheaper and needing less energy than traditional drinking water systems. The potential for low energy use and minimal operating costs was something that could be found in literature, though the sources in literature also make clear that not all storm- and rainwater recycling systems share those qualities, and it depends on how the system is designed (Fredenham et al. 2020; GRAF 2021). The systems at Celsiushuset and Wikholm were the best examples of this, both of them using rainwater gathered from rooftops with little treatment and contrary to LBVA also having sufficient storage. This was not uniform, however. Broadly, those that operated storm- and rainwater recycling systems found them to be easy to operate and largely devoid of any issues.

There were many benefits to recycled storm- and rainwater not factored into the multi-criteria analysis. Such as how it can help reduce pressure on groundwater reserves, as well as reducing the need for more intensive water treatment needed to produce drinking water, such as lessening the use of chemicals commonly used to produce drinking water.

The sensitivity analysis did indicate that even if the spans were adjusted significantly and weighting was removed, that it would not change the result that storm- and rainwater recycling systems could perform well relative to drinking water systems, nor affect the wider trends. Individual systems were affected, but most still hovered around the ‘Average System’ and generally trended to be more sustainable than not, something that lends more credibility to the outcome of the multi-criteria analysis and helps to somewhat compensate for uncertainty with the data.

Conclusive remarks:

Overall, the most difficult question to attempt to tackle is: are these systems more sustainable than traditional drinking water systems? The answer to that question appears to be, at this moment, that it depends. The recycling of storm- and rainwater certainly has the potential to be so, and in some cases are demonstrably cheaper to build, operate and less energy-demanding than traditional systems. In other instances, it is less conclusive.

The simpler in design and nature, as well as the less treatment and pumping necessary, the better the system performs. Water that is collected at lower qualities, and as such needing more extensive treatment, or simply treated excessively can start to defeat the underlying purpose that the recycled water does not need to be treated to the standards of drinking water. The more advanced and costly the treatment, the less sustainable it becomes. Ensuring that the water when it is collected contains as few particles as possible becomes important to this end. Whether it means collecting water from clean surfaces, or from bodies of still water with less turbulent flows. In the case of Nye, water production would have been greatly improved if the water at the intake had been less turbulent and particles had been allowed to sediment.

Another factor that weighs into the sustainability of these systems greatly are the local conditions of the traditional water supply. In places like Denmark, where groundwater reserves are under strain from human use and have significant issues with contamination, finding alternative water sources becomes more of a necessity rather than merely a consideration of cost or carbon emissions. For individual homes and households, it may be impractical to design and install novel systems with pumps for fairly modest returns. For larger buildings, such as workplaces and apartment complexes, systems can be more easily scaled to provide water for more people. Because traditional drinking water systems are not homogenous in nature, places with an abundant and sustainably used source of clean water are in less need of alternative water, meaning the benefits derived from the recycling of storm- and rainwater are lesser.

5.1 Limitations

For the literature study, and especially for the more complex areas such as the juridical aspects, the process was complicated by the fact that this is a field that is swiftly evolving, especially in Scandinavia. For instance, there were new regulations in Norway that came into effect around the same time as of the start of the writing of this report, with new provisions in the Planning and Building Act. Additionally, the scope of the study did not allow for in-depth scrutiny in all areas covered, which means that some context or developments pertaining to various details covered may be missing.

Literature regarding storm- and rainwater recycling and its sustainability relative to drinking water in Scandinavia was sparse, and as such it was difficult to compare the results of this study with others. The studies that had been conducted were largely more conceptual and discussed storm- and rainwater recycling without delving into specific systems, or covered systems prior to them being installed.

The multi-criteria analysis was limited in great part by the data available, as all projects did not track everything that others did. As such, a number of estimations and approximations had to be carried out based on the available information. Furthermore, the method for which the projects were given their points was in part dependent on the data on hand. While what was average for traditional systems could be found for energy consumption, carbon intensity and operating cost, this was not the case for the average investment cost per cubic metre over intended lifespan. Nor did this study discover literature values for the availability of recycled storm- and rainwater. As such, the spans in which different values or gradings would apply were assigned based on what seems sensible in regard to the data on hand, and could have been subject to change if there had been more data available.

It is possible that the results would have differed with more than five complete sets of data, although the broader trends were not altered with different spans for the criteria and with or without weighting. Though precisely how these trends might have been impacted by a larger dataset is to an extent immaterial, as it was the aim of the study to see if the recycling of storm- and rainwater could be sustainable in Scandinavian conditions, not whether or not they always were.

A potential drawback of the multi-criteria analysis was also that there was a degree of dependence between the carbon emission intensity and the energy intensity, and though the weighting put a lower emphasis on carbon emission intensity, it could still have an adverse impact on the total score in particular. The choice was still made to include it owing to the significant variations in carbon intensity across different regional grids, which could vary by more than an order of magnitude. The total sums are as such better viewed as an indicator of performance, carrying with them the risk of energy intensity weighing more heavily than what was originally intended.

The definition of sustainability used in this study was fairly generalized and limited, used as such given the wide scope of the study and time constraints. The time constraints meaning that fewer parameters could be used given the quantity of systems, suiting a more limited definition of sustainability. Depending on which definitions of sustainability that are used, however, there could have been more emphasis on institutional sustainability separately of social aspects pertaining to the individual user. Here, the institutional aspects were largely bunched together under the wider net of social sustainability as social criteria were not included in the multi-criteria analysis. Furthermore, the choice to use a more general definition of sustainability and not specifically water-related ones reflected that the water here was strictly for non-potable uses and there was no wastewater used. It is nevertheless a limitation, as more exact definitions and more in-depth evaluation could have yielded more definite results.

5.2 Further research

The chief cause of uncertainty that might have been remedied by more time, was the relative lack of data available. With more complete datasets there would have been a clearer picture as far as how storm- and recycling systems in Scandinavia have performed. This study did manage to find that storm- and rainwater recycling systems can perform better than traditional drinking water systems on the basis which they were measured, but more datasets would help to answer the question as to how frequently that occurs.

Another point that was not fully explored was how the projected increased costs of drinking water might impact the relative performance of storm- and rainwater recycling systems quantitatively, and how much that may contribute to making the recycling of storm- and rainwater to be more sustainable.

6. Conclusions

Based on the results above, the following conclusions can be drawn.

- Storm- and rainwater recycling systems can make significant contributions to Scandinavian countries' water supply and work at different scales, from supplying individual buildings to entire towns with water.

- Storm- and rainwater recycling systems can be cheaper and less resource-intensive than traditional systems, but not always. For well-designed and simple systems, maintenance can be minimal.

- Although concrete targets specifying the level of ambition were sparse, the project owners that were interviewed overall reported satisfaction with how the systems had functioned in practice.

- Overall, the quality of the water was considered to be high, with some discolouration being the most frequently cited challenge. No strange odour was reported.

- The cleanliness and nature of the collection area influences the need for treatment greatly, the collection of water from green areas is not ideal from this standpoint. The chief challenge otherwise comes during the first flush after a period of drought.

- Investment costs can be a significant barrier to new installations, with the relative novelty of and lack of experience with the storm- and rainwater recycling systems contributing to increased costs.

- Simple design choices, such as the dimensioning of storage, can have significant impact on the efficiency of a system. It is crucial to ensure sufficient capacity for storage of water in order to make full use of the intermittent water supply. Sloping storage tanks and pipes that allow for back-flushing were important design choices that allowed for easier maintenance of the system, owing to the presence of small particles.

- The simpler systems, those utilising rainwater from rooftops with minimal treatment, appear to have performed best. Some of the purpose of storm- and rainwater recycling can be lost if the water is put through very advanced treatment, or in other ways designed to be more expensive and resource demanding than more simplistic solutions, as costs and treatment can then approach or even exceed that which is used to produce drinking water.

- The climate significantly affects performance, with snow inhibiting the collection of the water. As such, the efficiency generally decreases in Scandinavia, the further north and inland one goes. Regions with significant snowfall during the winter months as such cannot supply water throughout the entire year using storm- and rainwater recycling systems, absent means of melting snow and ice.

- Storm- and rainwater recycling can be integrated successfully with solar energy on rooftops, paving the way for dual-use of space like rooftops.

- The regulatory framework in Scandinavia, especially outside of Denmark, is still in a very nascent stage and uncertainties remain.

Overall, the recycling of storm- and rainwater in Scandinavia has promise for large scale deployment, and this thesis has helped to illustrate that it has the potential to be a sustainable source of alternative water. It does however show that storm- and rainwater recycling systems are not inherently always a better option, and systems must be evaluated on a case-by-case basis.

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8. Appendix

Appendix A

Projects in Sweden:

Celsiushuset

Figure A1: Google Earth, © 2023 Maxar Technologies

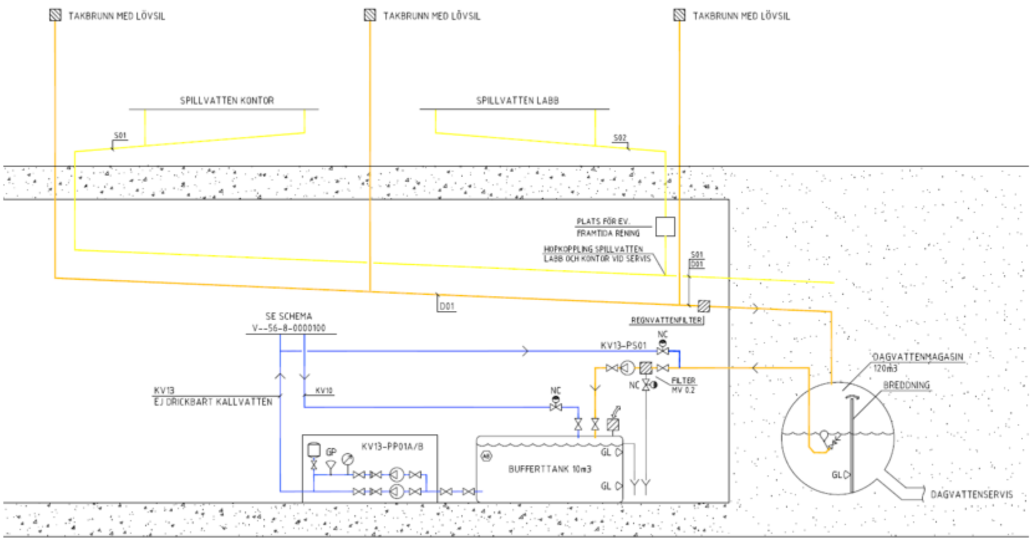

Figure 19: System schematic describing the water recycling system at Celsiushuset, © 2024 Vasakronan

Location: Uppsala

Owner: Vasakronan

Description: Originally conceived of as an idea in 2017, and taken into operation in 2020, this project consists of the office building Celsius that employs rainwater for the flushing of its toilets inside of the building. The purpose behind it being to promote water-efficient techniques to lower the consumption of drinking water.

End-use: WC (Flushing).

Collection: The building utilises a rainwater harvesting system through wells on the rooftop, as well as a small quantity from three downpipes connected to the building.

Treatment: The water is strained with a well-sieve to remove leaves and other debris, as well as a catchment well that allows heavier particles to sediment before it is taken to storage. Before use, the water itself is treated with a sandfilter and UV-disinfection.

Storage: An underground storage tank.

Distribution: Separate and marked pipes distributes the water to the toilets in the building, as to prevent any confusion with potable water.

(Vasakronan 2021)

Sergelhusen

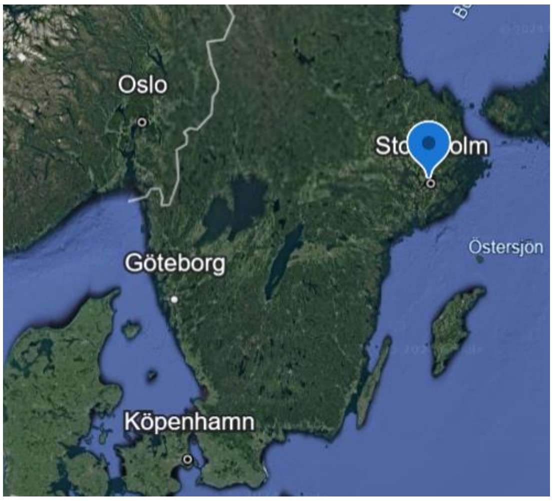

Figure A2: Google Earth, © 2023 Maxar Technologies

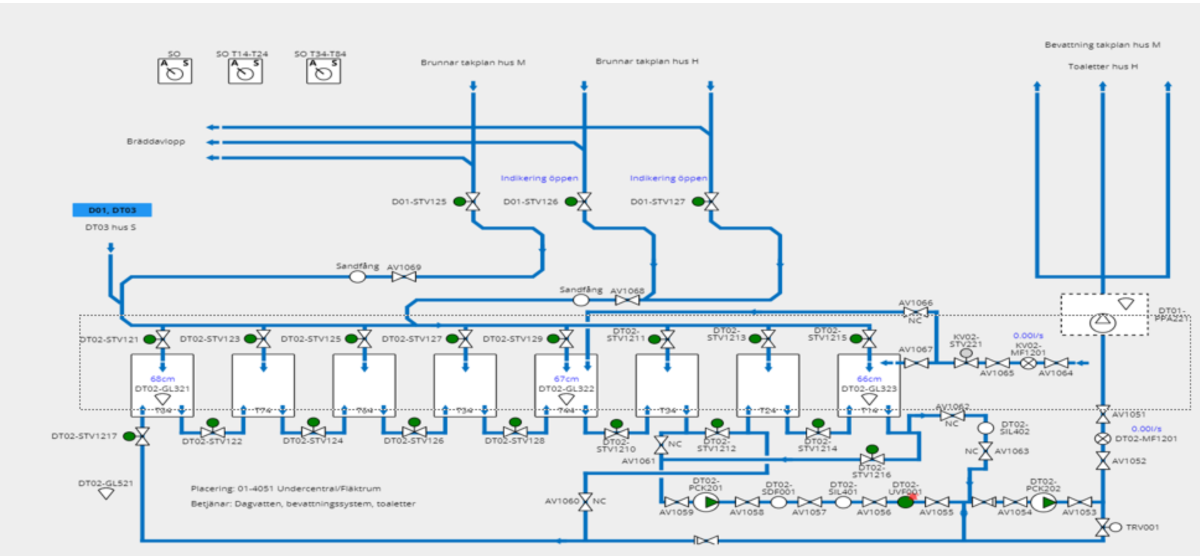

Figure A3: System schematic describing the water recycling system at Sergelhusen, © 2024 Vasakronan

Location: Stockholm

Owner: Vasakronan

Description: The office buildings, all adjacent to each other, are located in central Stockholm. Renovated since 2017, and taken into use in 2022. Rainwater is harvested and used for flushing and to water the green areas on the roof terraces, the terraces aimed at promoting recreation and biodiversity. The recycling of rainwater was part of a wider project of achieving sustainable practices within the building.

End-use: WC (Flushing) and irrigation of green areas.

Collection: A separate rainwater harvesting system is used to collect water on the rooftops.

Treatment: - Straining, glass, salt (turbidex), anion, ultra and activated carbon filters.

Storage: In-building storage tanks.

Distribution: A pipe system that distributes water to the toilets and the rooftop terraces.

(Vasakronan 2023)

Laholmsbukten VA

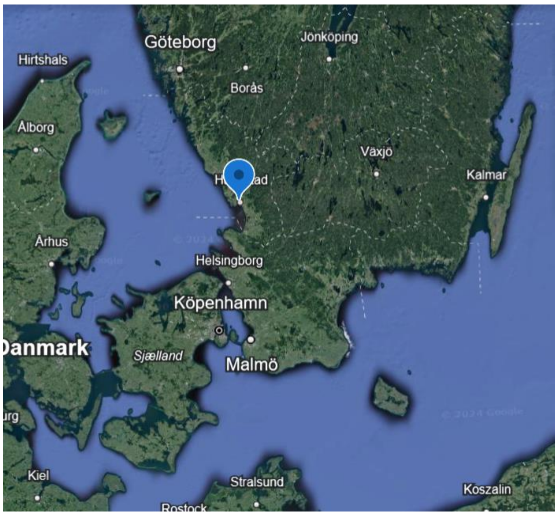

Figure A4: Google Earth, © 2023 Maxar Technologies

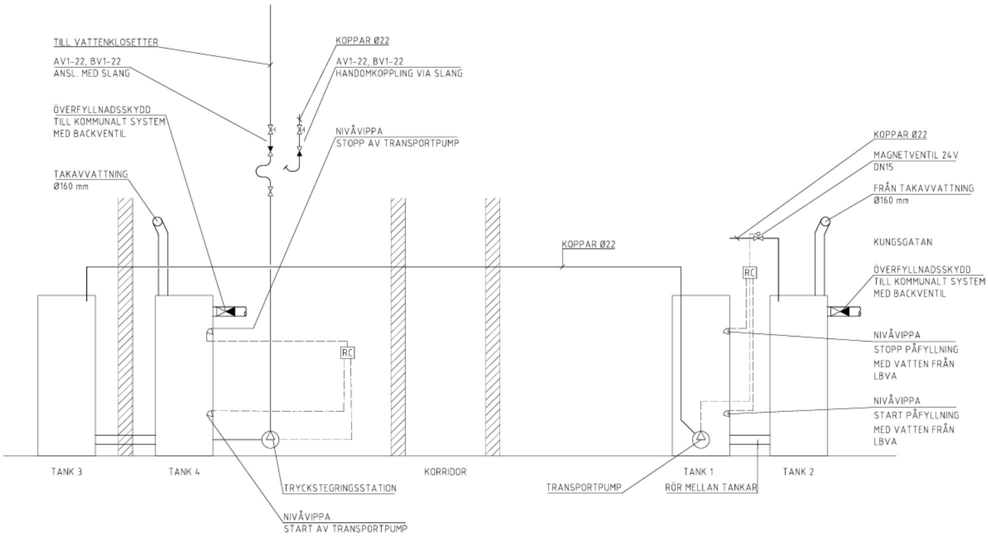

Figure A5: System technical plan describing the water recycling system at LBVA’s office building, © 2024 LBVA

Location: Laholmsbukten, Halland

Owner: Laholmsbuktens VA AB

Description: The office building for the local water utility company in Laholmsbukten installed a rainwater collection system, in order to use the water directly for the flushing of toilets inside the building, and as such decrease the need for drinking water.

End-use: WC (Flushing)

Collection: The rainwater is harvested through drainage on the rooftops, diverting it into downpipes that bring the water to storage.

Treatment: No treatment is used beyond straining through a rough filter.

Storage: In-building storage tanks.

Distribution: A separate system of pipes are used to distribute the recycled water to the toilets.

(Hallandsposten 2021)

Citypassagen Örebro

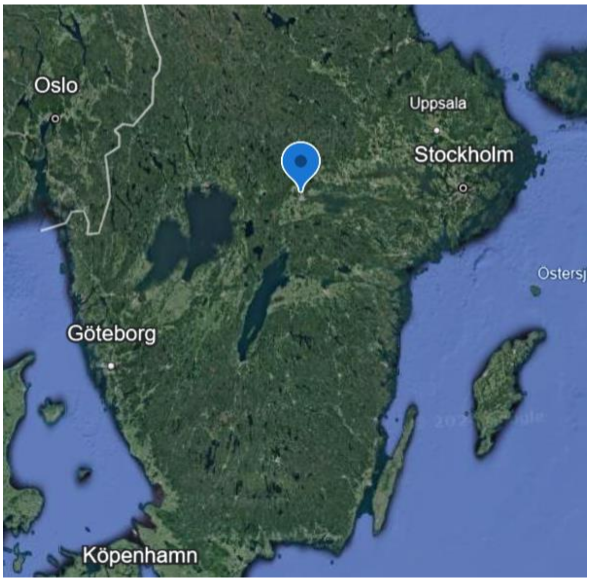

Figure A6: Google Earth, © 2023 Maxar Technologies

Location: Örebro

Owner: Castellum

Description: The project resulted from a cooperative project funded by the Swedish sea- and water authority, aiming to see how water-saving measures could be carried out in practice in both multi-family homes and office buildings. Rainwater harvesting systems were put in place in order to recycle water, and then employ it for flushing.

End-use: WC (Flushing).

Collection: The rooftops have had drainage wells installed from which the rainwater is collected.

Treatment: Sieves are connected to the wells, as to filter out leaves and other debris. For the water to be used for flushing, the treatment steps consist of a sandfilter, UV-disinfection and a microfilter (1µm).

Storage: There are two tanks for storage, one underground storage tank for the untreated stormwater, and a smaller in-building tank in the basement for the stormwater once it had been treated. The larger tank is connected to the municipal drainage system, should it overflow. The smaller is connected to the municipal drinking water distribution system should supply of water not match demand.

Distribution: A separate system of pipes are used to distribute the recycled water to the toilets.

Sockenstugan Stora Skedvi

Figure A7: Google Earth, © 2023 Maxar Technologies

Location: Stora Skedvi, Dalarna

Owner: Säterbo Bostäder

Description: The apartment building makes use of rainwater in order to flush the toilets on the premises, although it is connected to the municipal water supply, as to ensure it is always possible to flush.

End-use: WC (Flushing)

Collection: Rainwater is harvested from the rooftop and diverted to treatment from there.

Treatment: A three-chamber sedimentation tank is used to treat the water before it is led to storage.

Storage: Underground storage tank.

Distribution: A separate system of pipes are used to distribute the recycled water to the toilets, although the municipal water can be connected to this system by way of the storage tank.

(Säterbo Bostäder 2022)

Projects in Denmark

Holbæk Laundry Facility

Figure A8: Google Earth, © 2023 Maxar Technologies

Location: Holbæk

Owner: Elis, Fors A/S

Description: The chemical laundry facility at Holbæk employs recycled rainwater in order to wash the garments at the site, operating without need for drinking water. Furthermore, the facility can treat the wastewater once used, and reuse parts of it again, with roughly a fifth being lost in treatment through evaporation and sludge. The recycled water is supplied initially by FORS A/S, a local water utility company.

End-use: Laundry (Washing)

Collection: The facility uses a rainwater harvesting system, opening for collecting waters from other buildings too for use.

Treatment: Several filters, UV-treatment for disinfection and unspecified chemicals are used to treat the water.

Storage: In-building storage tanks.

Distribution: The water is distributed to the washing machine through a separate network of pipes.

(Elis 2019)

Nye City

Figure A9: Google Earth, © 2023 Maxar Technologies

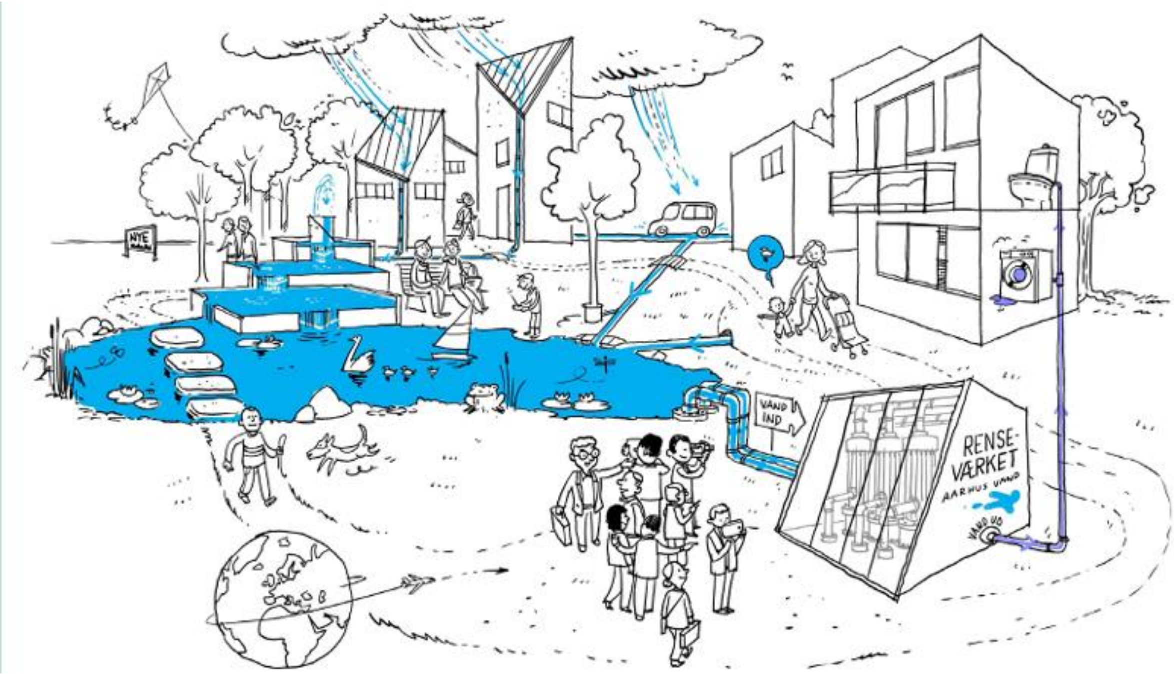

Figure A10: Illustration describing the water recycling system at Nye, © 2023 Aarhus Vand

Location: Aarhus

Owner: Aarhus Vand

Description: The recycling project is part of a wider plan in creating a sustainable city in Nye. Stormwater run-off and rain is collected and used for both the flushing of toilets and for use in washing machines. The aim is to eventually use this system for some 15 000 citizens, estimated to be housed in Nye in the long-term.

End-use: WC (Flushing) and Laundry (Washing)

Collection: Gutters and channels from both rooftops, soil and roads divert storm- and rainwater into storage.

Treatment: Nye has a small treatment plant consisting of a sandfilter, pressure filter, ultrafilter (<1 μm), and UV-disinfection.

Storage: Open storage in the form of a storm- and rainwater lake.

Distribution: A separate network of purple-coloured pipes divert the water for use, such that the distribution system is not confused with potable water.

(Aarhus Vand 2021)

Ramboll Headquarters

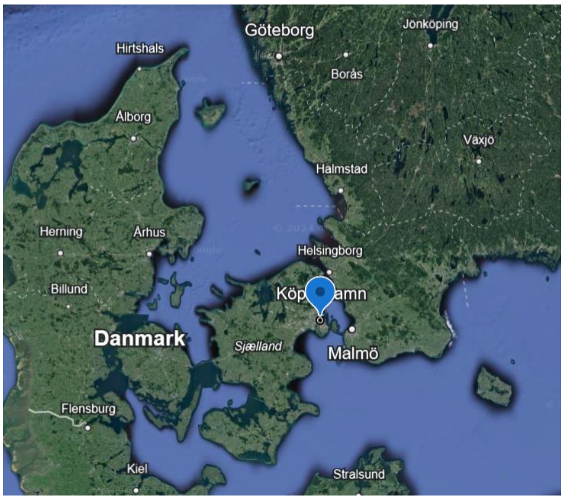

Figure A11: Google Earth, © 2023 Maxar Technologies

Location: Copenhagen

Owner: Ramboll

Description: The main office building of the consultant firm, Ramboll, utilises harvested rainwater for the flushing of toilets inside of the building.

End-use: WC (Flushing)

Collection: Rainwater is collected on the rooftop of the building.

Treatment: The only treatment used is straining through filters to remove leaves and larger particles, no further treatment is required before use.

Storage: An underground storage tank is used to store the treated rainwater.

Distribution: A separate system of pipes are used to distribute the recycled water to the toilets, although the storage tank is connected to the municipal drinking water distribution system, in the event of insufficient rainfall.

(Danva 2022)

Gårdhave Straussvej

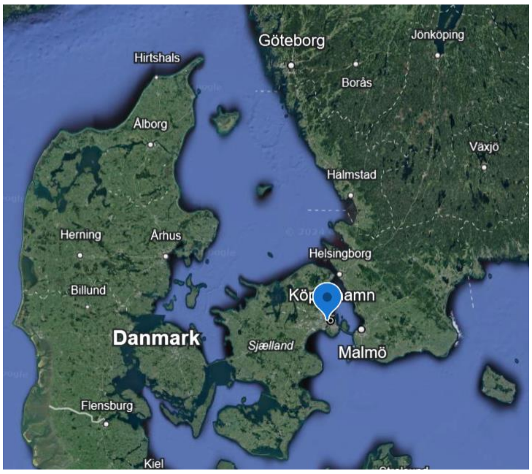

Figure A12: Google Earth, © 2023 Maxar Technologies

Location: Copenhagen

Owner: Copenhagen Municipality, HOFOR

Description: A small artificial and recreational lake in a residential area, created with harvested storm- and rainwater. Vegetation is allowed to flourish, and the water is made shallow to allow for small children to play in it. It is dimensioned to be able to cope with ARI 100 year flows.

End-use: Recreation (Lake)

Collection: Water is collected from the rooftops and led down by gutters to treatment.
Treatment: Biological treatment is used to ensure that the water is safe for human contact, such as children to swim in.

Storage: Open-storage serves the intended function of providing amenities in the form of recreation.

Distribution: A series of gutters and channels diverts the water to treatment, and then on to the artificial lake.

(Klimakvarter 2021)

Bispeparken

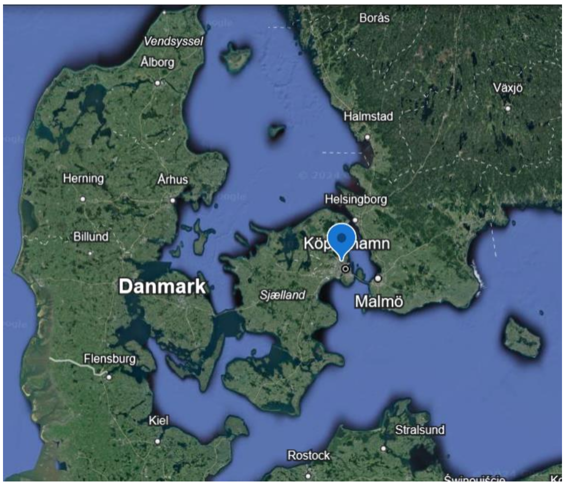

Figure A13: Google Earth, © 2023 Maxar Technologies

Location: Copenhagen

Owner: Bispeparken

Description: Rainwater is harvested from rooftops and balconies of residential buildings, before larger particles are strained, and it is diverted into storage. This water is then used for the washing of clothes in the residential buildings there. An artificial lake for excess water during very heavy rainfall, and a rain bed, also exists. Atop the rain bed, local biodiversity is aided through the creation of a green space there, accommodating for flora and pollinators.

End-use: Laundry (Washing) and recreation (artificial lake and green areas)

Collection: Rooftop rainwater harvesting through drainage.

Treatment: Only rough filtering for that which is intended to be used for washing. That which is allowed to infiltrate does however have a filter bed that removes zinc, brought with it by the water from the rooftops.

Storage: In-building storage tanks are used to store the water.

Distribution: Gutters are used to distribute the water to the rainbed, whereas a separate distribution system is used to transport the water from storage to the washing machines.

(Danielsen 2017)

Vaskeri Braband

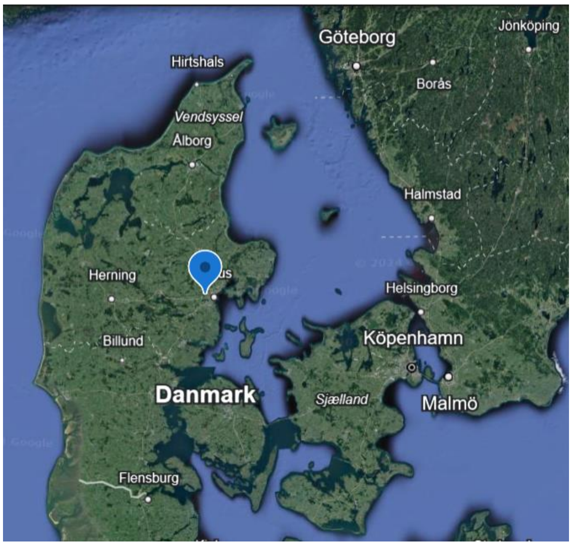

Figure A14: Google Earth, © 2023 Maxar Technologies

Location: Braband

Owner: Braband Boligforening

Description: Rainwater is used at the washery at Braband instead of tapwater for most of the washing, after having been harvested from the rooftop and treated with filtering techniques. The softer rainwater, having less lime in it, also brings with it the benefit of less soap having to be used.

End-use: Laundry (Washing)

Collection: The rainwater is harvested through drainage on the rooftops.

Treatment: Basic filters are used to strain larger particles from the water.

Storage: In-building storage tanks are used to store the harvested rainwater.

Distribution: A separate distribution system is used to connect the treated water with the washing machines.

(Jacobsen 2021)

Borupgård Gymnasium

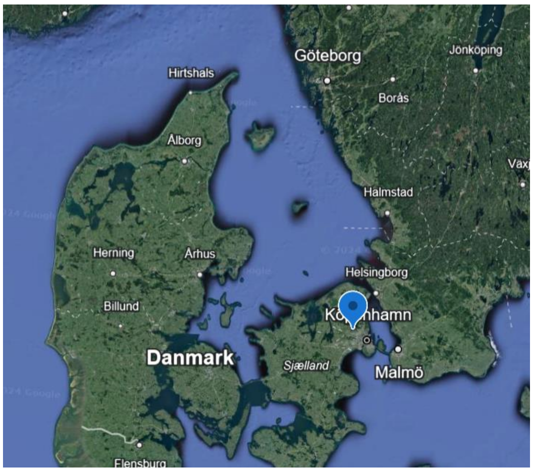

Figure A15: Google Earth, © 2023 Maxar Technologies

Location: Copenhagen

Owner: Borupgård Gymnasium

Description: The gymnasium installed a rainwater recycling system between 2019 and 2020 to decrease the use of drinking water there. Enabling the harvesting and treatment of the stormwater for the use of flushing in the gymnasium's toilets.

End-use: WC (Flushing)

Collection: A rooftop harvesting system is used, where the water is diverted into storage.

Treatment: No treatment is mentioned.

Storage: Underground storage tanks are used to store the water.

Distribution: A separate distribution system distributes the water to the toilets from the storage tanks, although the tanks in turn are connected to the municipal water supply in the event of a lack of rain.

(Ollgaard n.d.)

Sogn Hagelab

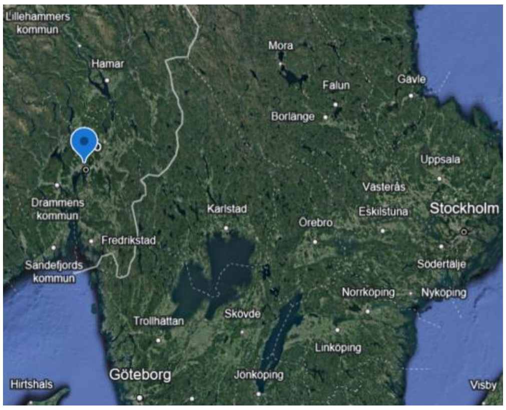

Figure A16: Google Earth, © 2023 Maxar Technologies

Location: Oslo

Owner: Sogn Hagelab

Description: Sogn Hagekoloni is a recreational area containing rental cabins and green spaces, and employs a quantity of various stormwater solutions. Rain beds, serving to create green areas in addition to flood protection, as well as rainwater harvesting systems for the use of irrigation of green areas, are two examples of the projects there.

End-use: Irrigation of green areas

Collection: Rainwater is harvested through rooftops and diverted into storage.

Treatment: Filters are used to strain larger particles from the water.

Storage: Above-ground storage tanks (plastic barrels) are used to store the water.

Distribution: A separate distribution system is used to distribute the water to the green areas.

(Sogn Hagelab n.d.)

Wikholm Anleggsgartner

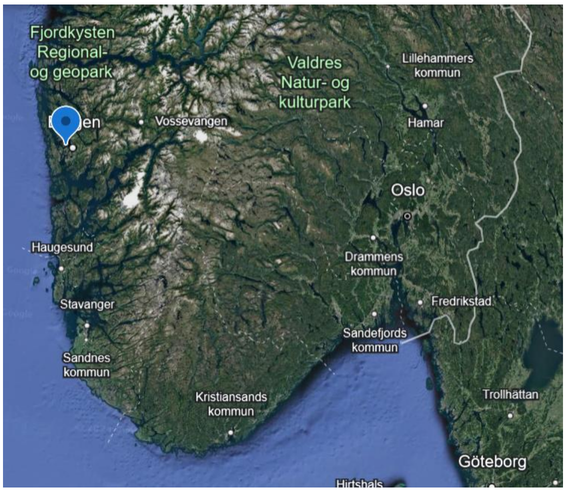

Figure A17: Google Earth, © 2023 Maxar Technologies

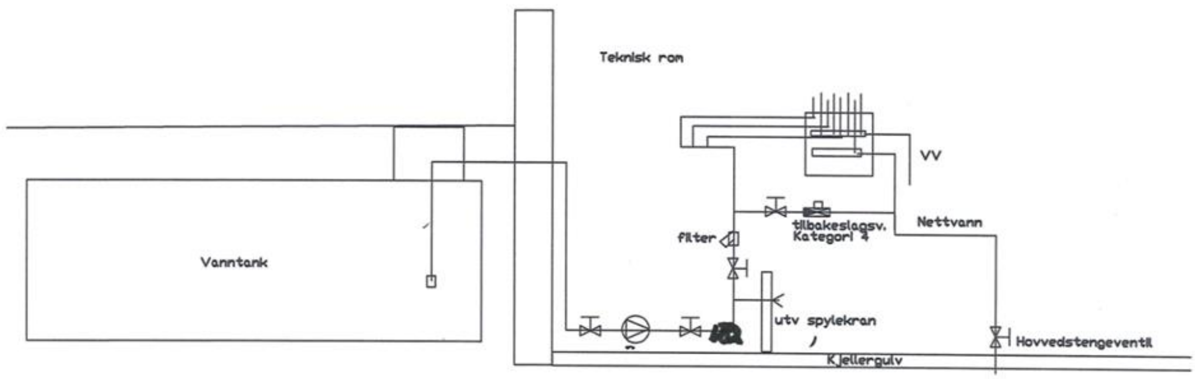

Figure A18: System technical plan describing the water recycling system at Wikholm, © 2024 Anleggsgartnermester Wikholm

Location: Bergen

Owner: Wikholm

Description: At Wikholm in Bergen, a landscape gardening firm, rainwater is collected and then used for both the flushing of toilets at their office building and warehouse. Additionally, the same system diverts water for the sweeping of streets, with broom trucks using the recycled water throughout the city.

End-use: WC (Flushing), irrigation of a garden, car-washing and the cleaning of streets.

Collection: Rooftop collection is used to gather the rainwater.

Treatment: Only simple filtration, owing to the cleanliness of the rooftops.

Storage: An above-ground storage tank is used to store the water.

Distribution: A separate distribution network is used to distribute the water from the tank, to its end-uses.

(Wikholm n.d.)

Nordox

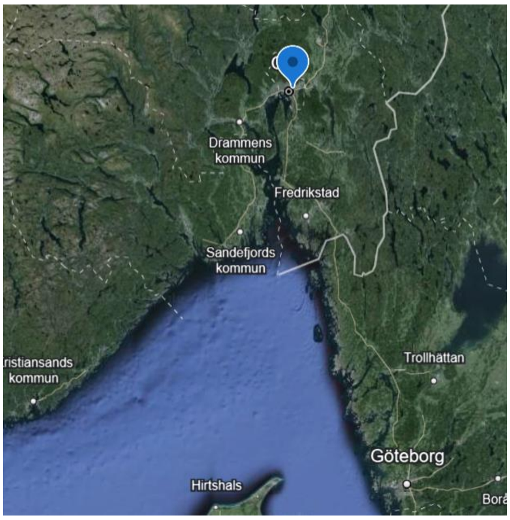

Figure A19: Google Earth, © 2023 Maxar Technologies

Location: Oslo

Owner: Ingenia

Description: In the factory of Nordox AS, stormwater is collected from rooftops and outdoor areas, only to be recycled and used as process water, therefore reducing the factory's need for clean drinking water. The process water does not need to be of potable quality for its uses and therefore the solution was deemed suitable by the company.

End-use: Industrial production (Process water)

Collection: The water is collected through rooftops and outdoor areas, where drainage is used to divert the water to storage.

Treatment: The water is not treated.

Storage: An above-ground storage tank is used to store the water before use. The tank is dimensioned to be able to store water even in the event of rainwater extremes, to be used during periods of sparser precipitation.

Distribution: A separate distribution network has been designed for the recycled stormwater, as to distribute it for the intended industrial processes.

(Ingenia n.d.)

Appendix B

Questions

Q1. What is your professional title?

Q2. Give a short description of what your role entails.

Q3. Why did your company choose to invest in circular storm- and rainwater solutions?

Q4. What was your ambition and purpose with the recycling of stormwater?

Q5. Are you content with the outcome? Has the project lived up to the ambitions?

Q6. Has there been any disturbances/difficulties or other issues with the system, or has it operated smoothly in practice?

Q7. How has the quality of the water been perceived by the users, has there been any issues with colour, odour or anything else?

Q8. Are there any particular lessons that you have learned now that the project has been carried out, anything that would have been done differently?

Q9. Do you have any schematics or pictures of the system that I might use in the report?

Q10. Any other material on hand that you would like to share? For instance, were any microbial or pollutant tests conducted?

Q11. How pressing do you consider it to be to work with circular storm- and rainwater solutions?

Q12. Are there ambitions to invest more in storm- and rainwater solutions in your organisation?

Q13. Is there political will behind storm- and rainwater solutions in your area, did you receive any support from municipalities or other authorities?

Parameters:

Energy consumption of the system [kWh/year]

How much water a year does the system produce? [m3/year]

What share of your water consumption in a year can be provided by the system? [in %]

What was the investment cost for the entire project? [EUR]

What is the operating cost for the system on a yearly basis? [EUR/year]

Availability, how often during the year is the system in operation and able to provide water? [in %]

When was the system taken into operation, and how long has it been in operation since then? (Have there been any pauses?)

What is the intended life expectancy of the system? [years]

What manner of collection and storage does the system have?

If you have any form of water treatment, how is the treatment system designed?

What dimension does the system have, and how much capacity does your storage have? (m3)

Appendix C

Celsiushuset:

The water recycled was estimated as 60% out of an estimated 1570 cubic metres per year in water consumption estimated in an earlier report (Söderqvist 2021) for Celsiushuset.

For Celsiushuset in Uppsala, the cost of electricity was used to provide a baseline for operating costs, with power prices averaged over the last year used to provide an estimate of the costs, at roughly 0.102 EUR/kWh. With additional fees and taxes not included (Uppland Energi 2024). Furthermore, 0.54 SEK/kWh, or 0.047 EUR/kWh was added as per the electricity tax for 2024 (Swedish Energy Market Bureau 2024).

As the system has operated smoothly and no maintenance has been necessary as of yet, the energy consumption of the pumps with its associated cost of electricity was used to represent the operating costs, with other consumption of energy deemed negligible by the stakeholder that installed and operates the system.

LBVA:

Though there was no information as to the energy consumption that the stakeholders had on hand, the effect with which the pump was operating was known. In consultation with Juha Metso[4] at Xylem, the manufacturers of the pump, and product-specific flowcharts. The flow at which the pump operated at 0.55 kW (with the engine it had installed) was roughly estimated at 0.75 l/s, or 2.7 m^3/h.

As the system recycled 100 m^3/year, this allowed for the calculation of the energy use over a year.

Time in operation = $\frac{100\ [m3/year]}{2.7\ [m3/h]}$ = ~37 [h/year]

[4] Juha Metso, Sales Department at Xylem, 2024-03-07

Energy use: 0.55 [kW] × 37 [h/year] = ~20 kWh/year

Power prices, excluding taxes and other fees, in the area averaged 0.74 SEK/kWh in 2023 (Elbruk 2024). With taxes, cost of electricity is 1.28 SEK/kWh, or 0.11 EUR/kWh (Swedish Energy Market Bureau 2024).

Much like for Celsiushuset, as the system does not have many components that could reasonably contribute to operating costs, the system runs without issue, and the owner could not estimate operating costs on their own, the price for the electricity needed to run the system was used to represent the operating costs. The assumption was made that personnel costs, maintenance and the replacement of material was minimal through the lack of such things as described by the owners during the interview. In the case of LBVA, there is no particular treatment besides a rough filter, further minimising operating costs.

Nye

Given that Nye was the largest of the systems and more complex, there were additional costs that were factored into the calculation of the operating costs for the owner. This included heating of the water, the costs of laboratory tests for the recycled water as well as various forms of maintenance, with downpayment from the investment portion being excluded from the operating cost. These were added together and converted to Euros from DKK. Additionally, the cost for rent for the city of Nye (constituting a very significant portion of reported operational costs for Nye) at large was excluded, as it was deemed not strictly related to the water recycling system.

Appendix D

Table D1. The systems when assigned values for each parameter in accordance with Table 14,with weighting.

Functional Units: \ Projects:	Celsius-huset	LBVA	Nye	Ramboll	Wikholm
Energy intensity [kWh/m^3]	1	2	2-3	4	1
Carbon emission intensity [gCO$_2$/m^3]	0.5	1	2	2.5	0.5
Cost of water [EUR/m^3]	1	1	2	2	2
Investment cost per cubic metre over intended lifespan [EUR/m^3]	4	10	8	6	36
Availability [%]	3	4	1	1	1

Table D2. The systems when assigned values for each parameter in accordance with Table 17, with weighting

Functional Units: \ Projects:	Celsius-huset	LBVA	Nye	Ramboll	Wikholm
Energy intensity [kWh/m^3]	1	2	3	4	1
Carbon emission intensity [gCO_2/m^3]	0.5	1	2	2.5	0.5
Cost of water [EUR/m^3]	1	1	2	2	2
Investment cost per cubic metre over intended lifespan [EUR/m^3]	6	10	8	6	6
Availability [%]	4	5	1	2	1