Rainwater Harvesting: A Study on Gravity-Driven Ceramic Membranes for Non-Potable Water Use

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Rainwater Harvesting: A Study on Gravity-Driven Ceramic Membranes for Non-Potable Water Use

by

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Picture on front page: The pilot scale membrane facility at Kemicentrum. Photo by Oscar Braun

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Preface

This master thesis was written at Lund University, Faculty of Engineering, at the division of Chemical Engineering at Kemicentrum. Experiments were performed in the Apparatus Hall at Kemicentrum. This thesis was performed and written between the 15^{th} of January 2024 and the 14^{th} of May 2024.

First and foremost, would I like to express my gratitude to my co-supervisor *Tobias Hey*. Without your ambition and encouragement and German temper I might not have been able to perform this project. Thanks for your professional guidance, our discussions and especially your uplifting comments during the entire semester. Thanks also to my supervisor *Frank Lipnizki* for encourage me to learn about membranes and thank you for your valuable feedback and support. Without the both of you and your expertise, the writing of this thesis would have been much harder.

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Populärvetenskaplig sammanfattning

Gravitationsdrivna keramiska filter möjliggör användning av regnvatten i toalettstolar och tvättmaskiner

Genom att använda regnvatten kan den dagliga dricksvattenanvändningen minska med ca 30%. Regnvatten kan samlas in i vattentankar och filtreras genom nedsänkta mikrofilter membran. Membranen som drivs av det gravitationsskapade vattenpelartryck i vattentanken ger redan vid 15 cm vattenpelare 9 L/min vilket möjliggör en toalettspolning varje minut.

Varje dag förbrukar vi i genomsnitt 140 L livsmedelsklassat dricksvatten per person i Sverige. Av dessa 140 L står toalettspolning för 30 L och klädtvätt för 15 L. Med fler torra somrar och brist på vatten både i Sverige och i övriga världen ökar trycket på att säkra dricksvattentillgången. Samtidigt drabbas vi av allt mer intensiva skyfall som ger översvämningar som riskerar att förorena våra vattenreservoarer och förstöra egendomar. En lösning på ovannämnda problem är att dra nytta av regnet. Genom att samla in regnvatten ges avloppen mer tid att ta hand om vattnet samtidigt som det insamlade regnet kan användas i våra hushåll även när tillgången till dricksvatten är sämre. Vattnet i våra toalettstolar och det till våra tvättmaskiner kräver inte samma hög kvalitét som vattnet vi dricker och istället kan regnvatten användas. På så vis tas ett steg mot en mer hållbar vattenanvändning.

På Kemicentrum i Lund installerades en anläggning för insamlande av takavrinning för att ersätta dricksvattnet i två toalettstolar. För varje millimeter regn som faller på takets yta kan ca 270 L takavrinning samlas in. Regnvattnet som samlades in från taket och ner via stuprännor in till anläggningen var grumligt och illaluktande. Det renades upp genom att tryckas igenom ett keramiskt plattmembran med hjälp av trycket från vattenpelaren över membranet, skapat av gravitionskraften. Membranet fungerar som ett mycket fint kaffefilter. Vatten passerar igenom membranet medan de oönskade partiklarna stannar kvar. Det renade vattnet samlades i en egen tank och pumpades sedan in till toaletterna med en pumpautomat.

Resultaten från undersökningen visar att membrananläggningen ger ett genomskinligt och luktfritt vatten som redan vid 15 mbar motsvarande ett vattentryck från 15 cm vattenpelare klarar av att täcka toalettspolningsbehovet. Med detta tryck kan en spolning ske varje minut och vid större vattenpelare går filtreringen ännu fortare. Genom att använda regnvatten sparas det 6 L vatten per spolning som görs med toalettstolarna och ca 60 L vatten per tvätt.

Ett förslag till uppskalning av anläggningen för att ersätta dricksvattnet i Kemicentrums samtliga toalettstolar och tvättmaskiner togs fram. Resultatet visade att Kemicentrum skulle kunna spara runt 2 600 m^3 dricksvatten årligen. För detta skulle det krävas att regnvatten från Kemicentrums två största parkeringsytor samt ca 20% av takytan leds om till en nedgrävd uppsamlingstank varifrån regnvattnet filtreras och pumpas in till fastigheten. Då kan hela Kemicentrum förses med dagvatten även under årets torraste månader. Med en investeringskostnad omkring 5,3 MSEK och teknisk avskrivning i 20 år gör att kostnaden för det renade regnvattnet hamnar omkring 90 SEK/m^3.

Summary

How can our water consumption become more sustainable? How can our consumption of drinking water decrease? With increasing temperatures, climate changes, and population growth the questions becomes more important. To address this, a suggestion of reducing our drinking water consumption by utilizing rainwater is proposed. Rainwater can be used to flush our toilets, to wash clothes, and for irrigation. How do we harvest rainwater?

A gravity driven pilot-scale membrane facility has been installed at Kemicentrum in Lund consisting of two collection/storage tanks, one membrane tank and a permeate tank. Rooftop runoff from approximately 300 m^2 was collected through the gutter system, redirected to the facility. The facility has a capacity of storing 5 m^3 raw rainwater and 1 m^3 filtered rainwater. The membrane is a ceramic silicon carbide membrane, consisting of 42 flat sheets with 0.1 μm pore size and a total 6.9 m^2 membrane area, submerged in a tank with rainwater. The facility is entirely driven from the hydrostatic pressure from the water level above the membrane making the process uncomplicated and energy cheap. No pumps are required except an automatic pump which supplies two toilets with filtered rainwater by demand. During the study no cleaning of the membrane have been needed and hence no chemicals have been added to the system.

In this study, the membrane performance with tap water and rainwater have been compared in terms of hydraulics and an analysis of the physico-chemical properties of the water before and after filtration have been conducted.

The results from the physico-chemical analysis of unfiltered and filtered rainwater showed that the raw rainwater contained suspended particles, low pH, turbid appearance, and bad odor. The filtered rainwater was transparent and had a neutral pH and no odor. The hydraulic analysis showed that flux and permeability increased with increased water head. The ceramic membrane operated with hydrostatic pressure successfully filtered rainwater which has successfully been flushed in the two toilets connected to the facility without apparent differences to potable water.

Moreover, the results from the pilot have been used to provide a proposal for scaling the facility for the entire Kemicentrum. By installing a collection tank with a volume of 120 m^3 and collect the rainwater runoff from both parking lots and part of the roof at a total area of 10,000 m^2 the flushing in all toilets and water to washing machines could be supplied with filtered rainwater the whole year around at Kemicentrum. By this wastewater treatment plants could be relieved at the same time as less potable water could be used. The water consumption at Kemicentrum could thus be more sustainable.

Sammanfattning

Hur kan vår vattenanvändning bli mer hållbar? Hur kan vi minska vår förbrukning av dricksvatten? Med stigande temperaturer, klimatförändringar och ökande befolkning blir dessa frågor allt viktigare. Ett förslag är att dra ner på vår dricksvattenkonsumption genom att använda regnvatten. Regnvatten kan användas till att spola i våra toalettstolar, till tvättmaskiner och till bevattning. Men hur kan regnvatten samlas in?

En membrananläggning i pilotskala driven av gravitationskraft har installerats på Kemicentrum i Lund, bestående av två insamlings-/lagringstankar, en membrantank och en permeat tank. Regnvattnet är takavrinning från ca 300 m^2 takyta som samlades in via stuprören som letts in till anläggningen. Anläggningen har en volymskapacitet på 5 m^3 för lagring av ofiltrerat regnvatten samt 1 m^3 för filtrerat regnvatten. Membranet är ett keramiskt plattmembran av kiselkarbid med en porstorlek på 0,1 µm. Membranmodulen består av 42 plattor med en total membranarea på 6,9 m^2 och är nedsänkt i membrantanken. Anläggningen drivs helt av det hydrostatiska trycket som uppstår från höjdskillnaden mellan vattennivån ovanför membranet och vattennivån i permeattanken, vilket gör processen okomplicerad och energibesparande. Den enda elektriciteten som används är en automatisk pump som försörjer två toaletter med filtrerat regnvatten efter behov. Under studien har ingen rengöring av membranet behövts och därmed har inga kemikalier tillsatts i systemet.

I denna studie har membranets prestanda med rent vatten och regnvatten jämförts och en analys av vattnets fysikalisk-kemiska egenskaper före och efter filtrering har utförts.

Resultaten från den fysikalisk-kemiska analysen av ofiltrerat och filtrerat regnvatten visade att regnvattnet innehöll partiklar, vilket gjorde att regnvattnet hade ett något surt pH-värde, grumligt utseende och dålig lukt. Det filtrerade vattnet var å andra sidan transparent och hade ett neutralt pH-värde och ingen lukt. Prestandatesterna visade att vatten kunde filtreras redan vid 15 mbar motsvarande vattenhöjd på 15 cm samt att fluxet och permeabiliteten ökade med ökande vattenhöjd. Det filtrerade regnvattnet har framgångsrikt spolats i de två toaletterna som är anslutna till anläggningen utan några uppenbara skillnader jämfört med dricksvatten.

Resultaten från pilotanläggningen har använts för att ta fram ett uppskalningsförslag av anläggningen. Ett förslag om att skala upp anläggningen för hela Kemicentrum har lagts fram. Genom att installera en stor insamlingstank med en volym på 120 m^3 samt samla avrinningsvatten från både parkeringsplatser och en del av taket motsvarande 10 000 m^2 kan spolningen i alla toaletter och vatten till tvättmaskiner försörjas med filtrerat regnvatten året om på Kemicentrum. Vid en sådan installation skulle vattenreningsverk kunna avlastas samtidigt som dricksvattenkonsumptionen skulle kunna minskas. Kemicentrums vattenanvändning skulle således kunna bli mer hållbar.

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1 Introduction

Potable water, or drinking water, is a versatile product not only used for drinking but also for agriculture, industries, and livestock. With the global population steadily on a rise, the demand for potable water escalates. Unfortunately, the water resources and distribution systems in many countries are struggling to keep pace with the rising demand (United Nations, n.d.). As the population grows, the pressure on available freshwater resources intensifies and the potable water are becoming more scarce and it's estimated that 40% of global freshwater resources will fall short by the year 2030 according to United Nations (2016).

To further complicate the dilemma, UN Water (n.d.) highlights the climate change. Climate change disrupts the pattern of precipitation, giving rise to more flooding, more frequent and intense extreme weather events, and droughts. Floodings can contaminate our surface water resources with salt water and bacteria which put pressure on the water treatment plant to handle (UN Water, n.d.). Sweden is experiencing these impacts, with rainfall in 2023 exceeding normal values from 1990-2020 by 90-130% (SMHI, 2024c) and increasing reports of floods and droughts.

According to VA SYD (2023b), the drinking water supplier in Lund, a more efficient and sustainable water consumption of the water resources must be obtained to handle the rise of water demand connected to the increasing urbanization and climate challenges. A promising solution is to reduce the potable water demand by replacing it with non-potable water where it is suitable. Irrigation, toilet flushing and washing are examples of areas suitable for non-potable water, such as rainwater. Toilet flushing and washing clothes contribute to consumption of 30 L and 15 L potable water per person and day respectively (VA SYD, 2023a). Using rainwater for toilet flushing can save up to 30% of the drinking water demand with further saving if also used for washing (Kusumawardhana *et al.*, 2021). Rainwater is seen as a potential replacement to potable water in toilets and washing machines to both save drinking water but also reduce the use of detergents in washing machines due to rainwater's natural softness (Haq, 2017).

1.1 Aim

The aim of this degree project was to review literature about rainwater harvesting and present how membranes can be used to treat rainwater. Accompanied with literature review a pilot scale facility utilizing a silicon carbide microfiltration membrane was installed to filter rainwater collected from the rooftop of the Apparatus Hall at Kemicentrum in Lund. Additionally, the aim was to collect rainwater and analyze it before and after the membrane and investigate the performance of the membrane. The filtered rainwater was aimed to be distributed to two toilets for flushing and to a washing machine and the system was evaluated from a technical and economical perspective. With the gathered data from the pilot, the aim was to propose a scale up for the entire Kemicentrum.

2 Literature Review

Naturvårdsverket (2024), the Swedish Environmental Protection Agency expect climate change to bring a variety of challenges: increased precipitation across entire Sweden, noticeable droughts in southern parts, and elevated risk for flooding to mention some. In addition, intense rainfall events are projected to become more frequent, leading to challenges for infrastructure such as roads and drainage systems (Naturvårdsverket, 2023). To address these challenges, it is necessary to explore ways of utilizing stormwater to alleviate the heavy loads on infrastructure but also offload the water treatment plants (VA SYD, 2023b).

In a statistical review by Liu *et al.* (2021) they observed a significant increase in interest in rainwater treatment over the past 20-25 years. In 2020 alone, over 900 articles were published in Web of Science on the topic of 'rainwater treatment', with a focus on rooftop runoff and surface runoff. Following chapter will introduce the implementation of rainwater harvesting system both globally and in Sweden. Further, the introduction to membranes and their utilization possibility in rainwater treatment will be presented.

2.1 Global Rainwater Harvesting Systems

Water have always been vital for the human population. Throughout history climate changes have led to droughts and as consequence ancient civilizations migrated in order to find fresh water. For some civilizations in arid and rural areas the water scarcity led to the implementation of rainwater harvesting and collection system which ensured self-sustainability of water and led to their thrive (Akpinar Ferrand and Cecunjanin, 2014). Still today the scarcity of water tend to lead to implementation of rainwater harvesting systems. One clear example is the 'Millenium Drought' in Australia. From 2001 to 2009 the area around River Murray experienced low rainfall and infiltration which led to lake dry ups, irrigation restrictions and posed a threat to the drinking water supply in southern Australia. It led to several water management changes on both governmental and domestic level and today Australia is one of many countries where rainwater harvesting is common in households (Campisano *et al.*, 2017).

Campisano *et al.* (2017) further describe the situation in Asia where foremost Japan is prominent. In Japan, rainwater catchment systems are primarily installed on office buildings. In response to water scarcity and urban flooding challenges in the early 1980s local governments promoted water recycling and financially supported rainwater harvesting systems in urban public facilities. Consequently about 30% of these systems are installed in schools and universities, with storage tank sizes ranging from 8 m^3 to 1,000 m^3, while 15% are on larger buildings with tanks up to 1,500 m^3. Following the 2011's earthquake in Japan, there has been an increase in households installing rainwater harvesting systems. The household facilities typically has smaller tanks, around 1 m^3.

As per Campisano *et al.* (2017), particularly Germany has widely adopted rainwater harvesting in Europe. In Germany approximately one-third of all new infrastructure incorporates a rainwater collection system. One notable example is in Berlin, where the Daimler Chrysler Potsdamer Platz features a 3,500 m^3 large storage tank collecting water from 19 rooftops

(Villarreal and Dixon, 2005). The trend of rise in potable water prices has contributed to increased popularity in installing rainwater harvesting systems in Europe (Campisano *et al.*, 2017). In Nye, Denmark, rain- and stormwater are collected in full-scale for non-potable applications to the village forthcoming 15,000 habitants. The water management system will besides also prevent flooding and could potentially save up to 30 million liters of drinking water annually (COWI, n.d.). Other countries reported of rainwater harvesting systems are Denmark (Albrechtsen, 2002), France (Vialle *et al.*, 2012), Switzerland and, the United Kingdom (Campisano *et al.*, 2017) where they utilizes runoff for toilet flushing and washing purposes.

Another noteworthy example is the Bullitt Center in Seattle, USA. The office building is fully self-sustained on water. Rainwater collected from the roof undergoes filtration through a ceramic filter, UV disinfection, and chlorine treatment. With this system the Bullitt Center can use rainwater for all potable and non-potable purposes (Bullitt Center, 2013). In total the roof is dimensioned for collecting slightly more than 2 m^3 rainwater per day with a consumption of only 1.4 m^3 daily (Melin, 2015).

2.2 Rainwater Harvesting Systems in Sweden

Rainwater harvesting systems are not as widespread in Sweden as in other countries. The cost of water in Sweden is still considerably low and the water accessibility is fairly high. However, in recent years sustainability, and water reduction have been brought attention to (VA SYD, 2023a) and VA SYD have through Jephson and Kristiansson (2023) written an inspirational guide for real estates on using storm- and rainwater. To this date, three large real estates are using storm- and rainwater to reduce their use of potable water. These, together with some local projects will be introduced below.

The newly constructed Celsiushuset, located in the city of Uppsala, in the middle east of Sweden, implemented a rainwater harvesting system. The rainwater is used for flushing the building's 42 toilets. On the roof of the 10,000 m^2 large office and laboratory building 20 wells have been installed. When it rains the rainwater is drained into the wells and flows down a gutter system into a 60 m^3 storage tank below ground. Prior the storage tank the water passes a sand filter separating mainly particles. From the storage tank the water is transported into a tank inside the building through suction. The water simultaneously passes a sand catch well which further separate particles from the water. The water inside of the building passes through a UV-light treatment and slow sand filters which disinfect and remove organic matter before storage in a tank from where flush water is taken. Celsiushuset reduces the consumption of potable water with 60% with this solution (Sweden Green Building Council, n.d.; Holm and Schulte-Herbrüggen, 2021). The installation cost was about 800,000 SEK according to Jephson and Kristiansson (2023).

Another project is Citypassagen, an office building in Örebro (Holm and Schulte-Herbrüggen, 2021). The house is dimensioned for 1,200 workers and 72 toilets and is estimated to consume 1,400 m^3 rainwater per year. Their storage tanks are 180 m^3 (Holm and Schulte-Herbrüggen, 2021) and uses sand catch wells, UV-light, slow sand filter with glass marbles and a 1 µm bag filter as treatment to remove bacteria, microorganisms, organic matter as well as disinfecting (Liljenskog, 2024). Citypassagen has reduced their potable water consumption with almost

80% 2019 and 60% 2020 (Holm and Schulte-Herbrüggen, 2021). Citypassagen's rainwater harvesting system cost about 1.2 million SEK to install (Jephson and Kristiansson, 2023).

In central Stockholm the building complex Sergelhusen is located, with a rooftop area of 6,000 m^2. When Sergelhusen was renovated in 2017 to 2020 a rainwater collection system was installed. With a capacity of storing 110 m^3 rooftop runoff in the basement of the building up to 50% of the daily water flush is done with rainwater. In comparison to Celsiushuset and Citypassagen, Sergelhusen has vegetation on the roofs which gives off a yellow-brownish discoloration to the water. An activated carbon filter clarifies and remove odor from the rainwater (Kretz, 2024) while sand filters separate particles and UV-light reduce microbial content (Jephson and Kristiansson, 2023). Further, Sergelhusen has flocculation, a 5 µm filter, a 1 µm filter and a 0.02 µm filter to remove iron, turbidity and color (Jephson and Kristiansson, 2023). No numbers of the installation cost has been reported.

Other rainwater treatment project are performed in southern parts of Sweden. VA SYD is leading the Swedish contribution in the EU-project Resilient Water InnovationEconomy (REWAISE). REWAISE is an innovation project with aims in reducing the consumption of potable water and using water in a smarter, more efficient way. The Swedish research is focusing on how water consumption can be improved. In Lund, the project performed a treatment of stormwater from a pond with membranes in a pilot scale. The results showed that membrane technology successfully removed microplastics, bacteria, and metals. Together with the knowledge gained in Lund, REWAISE's project has moved to Malmö where the project is under further development (REWAISE and VA SYD, n.d.).

In the area Sege Park in Malmö a new sustainable multi story car park has been built with a system for collecting rain- and stormwater from the rooftop as well as from the streets around the building. 1,720 m^3 per year could be claimed from the rooftop and an additional 9,300 m^3 from the streets (Jephson, 2023). The water is stored in an underground storage tank of 100 m^3 and will be used for irrigation of the vertically climbing plants covering the outside of the building (REWAISE and VA SYD, n.d.). The water demand is approximately 3,500 m^3 per year. Yet no compilation of the total cost has been published (Jephson and Kristiansson, 2023).

Another project in Sege Park is the work with the collective house Röda Oasen. At Röda Oasen VA SYD have installed a 70 m^3 underground tank where stormwater from roof and ground is collected. The collected water is pumped into a silicon carbide membrane (Cembrane A/S, Lynge, Denmark) facility inside the house and then supplied to the house's toilets, washing machines and the irrigation system. About 375,000 L of drinking water is annually saved by the installation (REWAISE and VA SYD, n.d.).

3 Theory

3.1 Contaminations in Rainwater

Rainclouds arise from evaporation of water from lakes and oceans, in that way rainwater is a result of a natural distillation process. Hence, the quality of rainwater is good when it first leaves the cloud (Thomas and Martinson, 2007). While falling from the clouds rainwater get in contact with airborne chemicals. When the rain falls from the sky it absorbs atmospheric gases (e.g. CO_2, NO_x, and SO_x). The gases dissolves in the rain, and with oxygen present, they form acids which decreases the pH in the rainwater (Haq, 2017). The contamination is geographically dependent so near the coast the rainwater may have dissolvement of salt and in urban areas pollution from NO_x is vastly higher than in rural areas due to exhaustion from combustion engines which further decreases the pH of rainwater in cities. In areas close to industrial sites concentration of air pollutants might be higher (Haq, 2017; De Buyck *et al.*, 2021).

Aside from the air contamination the water will also be contaminated by the catchment surface. Bird feces, dead rodents, and insects as well as dissolution of the material itself contribute to contamination of the water. The contamination can cause odor, contribute to microbial growth and spread diseases (Haq, 2017). Currently there is no regulation, policies, or guidelines for utilizing rainwater in Sweden (Sörngård, 2024).

3.1.1 Microbial Contamination

Microbial contamination refers to contamination from microorganisms, animals, and vegetation. The presence of microbial contamination may lead to illness or undesirable colorization or smell. The constituent of microbial contamination is highly dependent on weather conditions and the specific geographic area. For instance, wind can transport contamination like pollen and dust, which individually are considered contaminants, but accumulation of them on the surface can promote growth of microorganisms. In particular dry periods are identified as contributing to this observation (Campisano *et al.*, 2017).

Microorganisms could also originate directly from animal feces, such as bird spilling. Fecal contamination by animals serves as carrier of pathogenic microorganisms, commonly bacteria like *E. coli*. The fecal microorganisms typically causes gastrointestinal diseases (Kusumawardhana *et al.*, 2021). Research by Kusumawardhana *et al.* (2021) on rooftop rainwater found the presence of pathogenic bacteria such as *Salmonella spp.*, *Legionella spp.*, *Pseudomonas spp.*, among others. These pathogens can cause diseases if ingested or inhaled. For non-potable applications there is less concern of pathogenic contamination as it would not be ingested, however *Legionella spp.* can still be transmitted but through aerosol ingestion, i.e. water droplets in the air which can be inhaled. The existence of pathogenic bacteria is a concern for human health indicating the need of treatment, which is reported also by Haq (2017).

An Australian study analyzing 204 water samples from 84 rainwater collection tanks revealed the risk of pathogen exposure through either drinking collected rainwater or aerosol ingestion from hosing or flushing. The study, conducted by Ahmed *et al.* (2010), showed that the risk of drinking the collected rainwater posed a large risk of infection. However, aerosol ingestion leading to infection from pathogenic bacteria like *Salmonella, Legionella* and *Giardia* was below the threshold value of 1 infection per 10,000 people per year. Conclusively, Ahmed *et al.* (2010) found that disinfection of rooftop runoff is necessary for potable applications.

Microbial contamination could also cause odors and discoloration of the water. Decomposition of algae under anaerobic conditions can lead to a tangible smell. Unpleasant smell could originate from dead rodents or insects which has ended up in the collection tank (Haq, 2017).

3.1.2 Chemical Contamination

Besides microbial contamination, there can be chemical contamination in the water. Chemical contamination in rainwater primarily arises from dissolution of minerals and heavy metals. As mentioned in the introduction to this chapter, air pollutants contribute to the slight acidity of water, promoting the dissolution of minerals and heavy metals on the catchment surface. The presence of minerals and metals depends on the material of the surface and the geological position, and the concentration of minerals are usually very low according to Haq (2017). As such, the calcium and magnesium content are lower in rainwater compared drinking water, constituting natural softer water, a desirable property as it reduces the need for detergents in washing (Haq, 2017; Faragò *et al.*, 2019). Heavy metals in collected rainwater generally comes from the catchment surface, pipes, or collection tank (Haq, 2017; Simmons *et al.*, 2001; Chang *et al.*, 2004; Lye, 2009). Simmons *et al.* (2001) found in a study of rooftop rainwater in New Zealand that the maximum lead, zinc, and copper level were exceeded set by New Zealand Drinking Water Standards. The permissible levels in New Zealand of lead is 0.01 mg/L and 2 mg/L for copper (Simmons *et al.*, 2001) which corresponds to the same levels set by the European Union (Livsmedelsverket, 2024a; Livsmedelsverket, 2024b). Chang *et al.* (2004) reports that rooftop runoff exceeded the standards set by the US Environmental Protection Agency regarding copper, lead, and zinc, in a study about roofs as a source of water pollution conducted in Texas 1997 to 1998. The permissible levels in the US was during the study, 0.013 mg/L for cupper, <0.065 mg/L for lead, and <0.120 mg/L for zinc (Chang *et al.*, 2004). Elevated levels of zinc, as mentioned by Lye (2009), may lead to symptoms such as nausea, stomach issues, and in some cases it has been associated with kidney and pancreas issues. Lead exposure, particularly concerning children, can result in neurological dysfunctions. On a contrasting note, heavy metals only pose a threat if ingested. Additionally, Thomas and Martinson (2007) emphasize that suspended heavy metals tend to sink to the bottom and form a sediment in storage tanks due to the relatively dense metals. This sediment has a low tendency of resuspension.

3.2 Membranes

A membrane serves as a physical barrier or filter, allowing passage of certain liquids while retaining molecules, particles, and other solutes (Foley, 2013), see Figure 3.1. Membrane technology has a wide range of applications from water treatment to pharmaceuticals, and the food industry. The separation of liquids and solids is pressure driven and commonly there are four types pressure-driven processes, microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO).

In MF, the separation is due to relative size of the particles and the filtration is mainly through sieving where particles larger than the pore size are retain due to size exclusion.

In UF, the separation is still due to size exclusion. However, in UF membranes water and particles of low molecular weight pass through the membrane while large molecular weight are held back by the membrane, why retention in UF membranes sometimes are defined by the so-called molecular weight cut-off (MWCO). MWCO is the molecular weight were 90% of the solute is rejected by the membrane (Koros *et al.*, 1996).

NF lies in the region between MF/UF and RO and the permeability is effected by both size and charge (Foley, 2013).

RO's main application is desalination of water. RO membranes are dense, meaning there is no detectable pores as per the IUPAC definition (Koros *et al.*, 1996). The dense membrane has a low permeability and the rejection of salt is mainly due to the ion charge rather than size (Foley, 2013).

The membrane used in this project is a submerged gravity driven MF membrane.

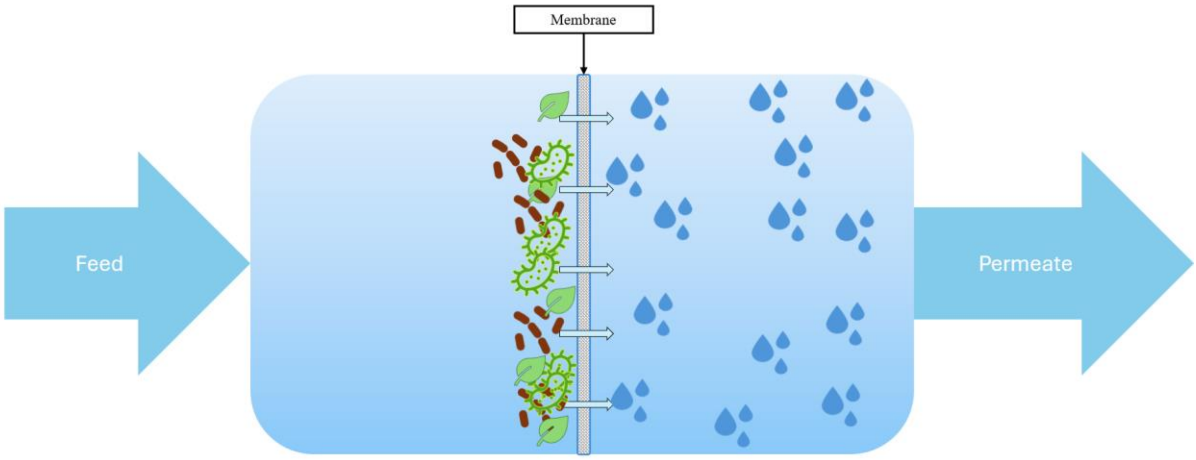

Figure 3.1. Simplified schematic overview of the principle of membrane filtration. Water and particles are feed from the left and only water is passing the membrane over to the right side while the rest is retained on the feed side of the membrane.

3.2.1 Membrane Classification

In Table 3.1 the operating pressures, pore sizes and retained species for the four common membrane processes are presented. Besides pore size, as mentioned above, it is common to describe the rejection of species in UF membranes by MWCO. The UF has the ability to retain macromolecules which are more commonly defined by their molecular weight rather than size. Therefore, UF membranes rejection is classified by MWCO. Membranes are affected by pressure drop. Small pores lead to a larger pressure drop and vice versa. MF has the largest pore size, experiencing the least pressure drop and reject large colloids and bacteria (Yang *et al.*, 2019). UF and NF have progressively smaller pores, with RO having the smallest pores. As the membranes are pressure driven the driving force decreases with an increase in pressure drop over the membrane. The applied pressure is dependent on the pore size of the membrane and in combination has to exceed the osmotic pressure of the solution. The osmotic pressure opposes the applied pressure and creates a backpressure (Foley, 2013).

Table 3.1. Classification of membrane technologies in terms of operating pressure, pore size and rejection.

Membrane technique	**Operating pressure (Foley, 2013)**	**Pore size (Yang *et al.*, 2019)**	**Rejection (Yang *et al.*, 2019)**
MF	0.5 – 3 bar	0.1 – 10 µm	Large colloids, bacteria
UF	1 – 10 bar	2 – 100 nm (or 1-200 kDa)*	All above + macromolecules, proteins
NF	7 – 40 bar	1 – 2 nm	All above + multivalent salts
RO	25 – 100 bar	0.1 – 1 nm	All above + monovalent salts

*(Jephson and Kristiansson, 2023)

3.2.2 Areas of Use

MF is commonly used in biological treatment, such as removing microorganisms or cells (Cheryran, 1998), achieving a substantial reduction in protozoa and coliforms, up to 6 log reductions (Warsinger *et al.*, 2018). MF can reject protozoa, bacteria, and large colloids at low hydrostatic pressures and obtain high flux and rejection (Liu *et al.*, 2021).

UF, with a pore size suitable for removal of macromolecular substances besides bacteria, suspended solids, and viruses, is well-suited for various applications such as water reclamation, wastewater treatment, and turbidity reduction for example (Singh and Hankins, 2016).

RO is commonly used for desalination of ocean water in areas where freshwater are in scarcity (Foley, 2013) however RO is also used in other water purification processes (Yang *et al.*, 2019). For instance, in electronics industry, and in food and beverage industry to concentrate dairy, juice and to remove alcohol in alcohol-free drinks (Wang and Wang, 2019).

NF are widely used in treatment of various water resources such as surface water, rainwater, groundwater, and seawater (Maroufi and Hajilary, 2023).

The membrane technologies have a broad use and sometimes several membranes are fitted to perform the same assignment hence overlapping boundaries are not unusual (Foley, 2013).

3.2.3 Ceramic and Polymeric Membranes

Membranes can briefly be divided into two categories, polymeric membranes, and ceramic membranes. Historically, polymeric membranes have been the preferred choice in water treatment applications. However, there is a growing trend of favoring ceramic membranes (Asif and Zhang, 2021).

Ceramic membranes consist of an inorganic material such as alumina or silicon carbide while polymeric membranes consist of organic material, either synthetic or natural polymers such as polyvinylidene fluoride (PVDF) or cellulose acetate (CA) (Sonawane *et al.*, 2021).

Ceramic membranes are more resilient to harsh chemicals and thus provides an extended lifespan compared to polymeric membranes. Furthermore, ceramic membranes exhibit a more narrowly distributed pore structure and has greater porosity compared to polymeric counterparts. The higher porosity results in higher permeate fluxes. In ceramic membranes a lower pressure can thus be obtained to achieve the same flux (Hofs *et al.*, 2011). However, the disadvantages of ceramic membranes are the comparably high capital expenses (CAPEX) in relation to polymers.

When designing a rainwater harvesting system one has to keep in mind the process operation. Since rainfall is intermittent, rainwater collection is considered a discontinuous operation. And due to seasonal variations there may be periods with no rainfall, resulting in temporary shutdown of the treatment system. Guillen-Burrieza *et al.* (2013) investigated the impact of allowing polymeric membranes to dry out between operations. The findings revealed the occurrence of scaling occurred on the membranes surface, leading to a reduction in membrane flux of the membrane. These results highlights the importance of maintaining the membrane in a wet condition to ensure optimal performance. Szabó and Anda (2018) came to similar conclusion investigating the storage conditions of the polymeric PVDF-based membranes. They explain that to protect the membrane and preserve the performance, it was necessary to immerse it in a glycerol-water mixture before storage. According to a patent by He and Blume (2004), a polymer membrane experiences a reduction in the permeability after drying out due pore collapse, and the use of glycerol may potentially modify the membrane's structure. Upon drying out, rehydration might cause irreversible damage to the membrane surface. This underscores the crucial importance of selecting what type of membrane to use in the system, as it could be crucial for the long-term performance of the treatment system.

3.2.4 Operation Mode

The separation in membrane technologies is commonly configurated in one of two different configurations: dead-end filtration, and cross-flow filtration. In dead-end filtration the solution is fed perpendicular to the surface of the membrane, similar to a coffee filter, which builds up a cake layer. Cross-flow filtration is operated with the feed tangentially to the membrane surface. With cross-flow mode fouling is reduced due to shear forces formed by cross-flow velocity close to the membrane surface. While dead-end filtration fouling can be prevented by for instance backwashing and air scouring which creates turbulence and reduces fouling, an example is presented in Figure 3.2. The membrane used in this project is operated in a dead-end configuration.

Figure 3.2. Illustration backwash mode (Cembrane A/S, n.d-b). Picture retrieved with consent from Cembrane A/S.

3.2.5 Submerged Membrane Filtration

Submerged membrane filtration is an approach where the membrane are submerged into the feed medium. Submerged membrane generally is operated in a dead-end filtration mode where the pressure is obtained from gravitational force and the filtration is continuous out-to-in (Peter-Varbanets *et al.*, 2010; Pronk *et al.*, 2019), see Figure 3.3.

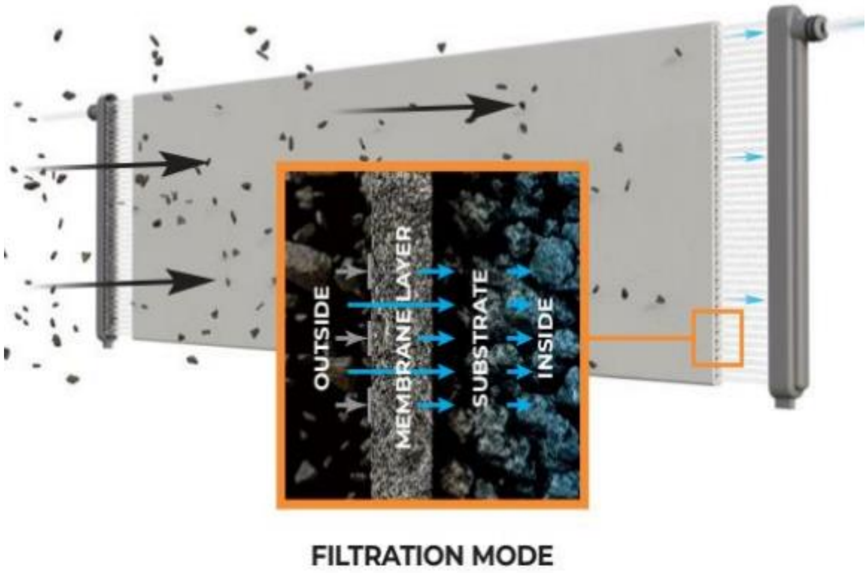

Figure 3.3. Illustration of outside-in filtration in flat-sheet membrane (Cembrane A/S, n.d-b). Picture retrieved with consent from Cembrane A/S.

The feed is drawn into the membrane by suction pressure and the rejected solids form a cake layer on the surface of the membrane. The substrate permeating the filter is collected in both ends of the membrane module permeate lines and runs through the top permeate manifold (Cembrane A/S, n.d-b). Submerged membranes are usually placed vertically and equipped with cleaning options such as air scouring or backwash, both of which provide shear across the membrane surface (Cembrane A/S, n.d-b). The operating pressure is commonly obtained hydrostatically generating low trans-membrane pressure. By having low operation pressure and effective fouling control the cost of energy and chemicals can be kept low (Pronk *et al.*, 2019) which offers a cheap filtration. Liu *et al.* (2021) and Pronk *et al.* (2019) points out that gravity-driven membrane processes shows good turbidity and bacteria removal without need of backwashing or chemical cleaning at hydrostatic pressures between 40-100 mbar.

3.2.6 Operating Parameters

The purpose of a membrane is for particles or *solutes* to be retained on one side of the membrane called *retentate*. The liquid permeating through is called filtrate or *permeate*. The driving force is pressure across the membrane, also called *trans-membrane pressure*, ΔP_{TMP} (Foley, 2013). For gravity driven submerged membranes, considered in this project, the trans-membrane pressure is defined as the hydrostatic pressure obtained from the height difference between the feed and permeate described in Equation 1. The pressure difference in this case is the hydrostatic pressure obtained from the height difference between the water column above the membrane manifold and the water level above the inlet to the permeate tank, see Figure 3.4.

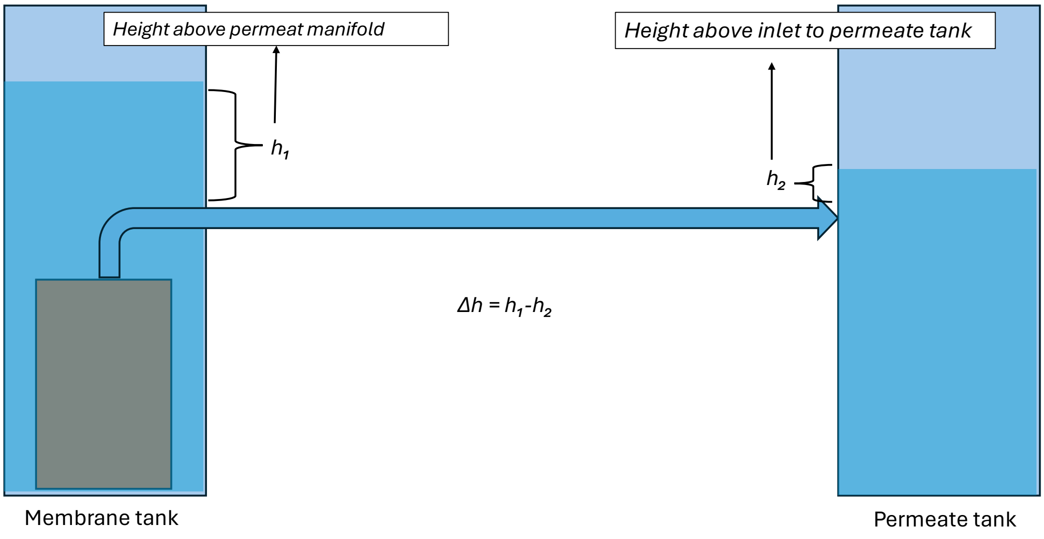

Figure 3.4. Simplified illustration of the pressure difference obtained from the height difference in the membrane tank and permeate tank.

$$\Delta P_{TMP}\ [bar] = P_{feed} - P_{permeate} = \rho * g * \Delta h \tag{1}$$

One important parameter for membrane filtration is the permeating flow, called *flux* or *permeate flux*, *J*. Flux is defined as the volumetric flow per membrane area and time (Foley, 2013).

$$J\ [L/m^2/h] = \frac{Q_p}{A_{membrane}} \tag{2}$$

Where Q_p is the volumetric flow rate (L/h) of the permeate and $A_{membrane}$ is the membrane area (m^2). Membrane performance could also be expressed as permeability, see Equation 3. The permeability of the membrane can be used to monitor the membrane's ability to transport water under a given pressure. (Cembrane A/S, n.d.)

$$Permeability\ [L/m^2/h/bar] = \frac{J}{\Delta P_{TMP}} \tag{3}$$

A challenge with membrane filtration is fouling. Fouling can be described as deposits on the surface of the membrane which reduces the performance of the membrane. Fouling can occur in different ways but commonly caused by organic and inorganic matter, colloids and microorganisms which led to a flux-reduction (Liu *et al.*, 2021). Fouling is synonym with an increase of membrane resistance which depresses liquid permeation. Fouling can occur differently, as for example by clogging of the pores, adsorption of particles on the membrane surface, cake formation or due to formation of gel by particles with gelation properties (Al-Rudainy, 2020; Foley, 2013). As response, periodic backwash, air scouring or other cleaning are used.

3.3 Rainwater Treatment with Membrane

Treatment systems are an integral part of the rainwater harvesting system in order to separate the water and the contaminants. The use of membranes in rainwater treatment is mainly allocated to MF and UF membranes. A couple of examples are presented in the following section.

At a parking lot in Brazil, Ortega Sandoval *et al.* (2019) separately investigated the performance of using submerged polymeric hollow fiber polyether sulfone UF (PAM Membranes, Rio de Janeiro, Brazil) and a hollow fiber polyimide MF (PAM Membranes, Rio de Janeiro, Brazil) for treatment of stormwater runoff. With a UF having 50 kDa and a pore size of 0.4 µm in the MF the facility filtered heavily contaminated runoff. The stormwater consisted of oil and grease, microorganisms, heavy metals, and larger dirt. The MF initially operated at 265 $L/m^2/h$ and stabilized at 60 $L/m^2/h$ while the UF was operated between 220 $L/m^2/h$ and 80 $L/m^2/h$. It showed that the MF membrane could remove 97% of the turbidity from average 65 NTU down to 2 NTU while UF could remove 99% from average 120 NTU down to 1 NTU. The membranes, however, showed low removal efficiency of the heavy metals lead, cadmium, chromium, nickel, and zinc while removing the copper completely. The permeate contained chromium which must be reduced further for irrigational use as it is toxic to plants. However, for toilet flushing purpose the need for further removal is not necessary according to Ortega Sandoval *et al.* (2019).

In Nye, Denmark, collected stormwater from rooftop runoff and surface runoff is treated with UF membranes together with pre-filter, sand filter and UV-disinfection. The collected rainwater in Nye are used for non-potable applications and it have been showed that the softness of the rainwater is lower than that of regular distributed drinking water (Faragò *et al.*, 2019).

Kus *et al.* (2013) investigated the performance of a pilot-scale gravity driven polymeric MF membrane (Ultra Flo) in Australia with 0.1 µm large pores in combination with a pre-treatment of granular activated carbon (GAC) (Watts) for 120 days. The flow was driven by hydrostatic pressure from an up to 2 m water head. The membrane had a membrane area of 0.4 m^2 and was operated with a flux of 27 $L/m^2/h$ which decreased over time due to fouling. During the experiment almost no backwashing was performed which led to flux deduction and the steady state flux of 0.47 $L/m^2/h$. The results showed that the GAC removed the turbidity in the water by about 80% and the membrane provided additional removal of turbidity for up to 20%. The raw water had a turbidity of 1.5 NTU and was reduced to 0.3 NTU in the effluent. Additionally, heavy metals were reduced below the Australian Drinking Water Guidelines.

Shiguang *et al.* (2021) investigated the use of a flat sheet gravity driven ceramic membrane (GDCM) to treat rooftop rainwater in lab-scale manufactured by ZhongQing Environmental Technology Co., Ltd, Shenzhen, China. The membrane was an alpha-alumina MF with a pore size of 0.1 µm and an active membrane area of 0.21 m^2. The system's initial flux was 168 $L/m^2/h$ and achieved a stable flux of 22-45 $L/m^2/h$ after two weeks of operation. The experiment was in no need of backwashing during the experiment's two months of operation. The GDCM was on average able to reduce the turbidity from 5.82 NTU to 0.46 NTU corresponding to a reduction of 92.2%. The system also reduced 61.0% of *Coliforms* and 96.9% of *E.coli*.

Park *et al.* (2020) compared the use of ceramic and polymeric membrane to treat a synthetic water. They used a disk-type zirconium dioxide (ZrO_2) and titanium dioxide (TiO_2) ceramic membrane (Sterlitech Co., WA, USA) and a flat-sheet polyvinylidene difluoride (PVDF) polymeric membrane (Millipore Co., CA, USA). Both tests were conducted as dead-end filtration. The results showed that both membranes were capable of reducing turbidity in the raw water from 60 NTU to 0.2 NTU. The high turbidity caused fouling on the membrane surfaces where it in the polymeric membrane caused irreversible fouling.

4 Materials and Methods

This chapter contains descriptions of the experimental setup, equipment and analytical methods used to determine membrane performance.

4.1 Experimental Methodology

4.1.1 Pilot-scale Membrane Facility at Kemicentrum

The experiment was conducted on a pilot-scale membrane facility in the Apparatus Hall at Kemicentrum. In brief, the facility is designed to be uncomplicated and compact and consisted of four tanks, a pump with pressure sensor, two toilets and a washing machine, in addition to pipes and valves. More details of the system is described below. In Figure 4.1, a simplified system outline is illustrated whilst in Figure 4.2, the facility in the Apparatus Hall is presented.

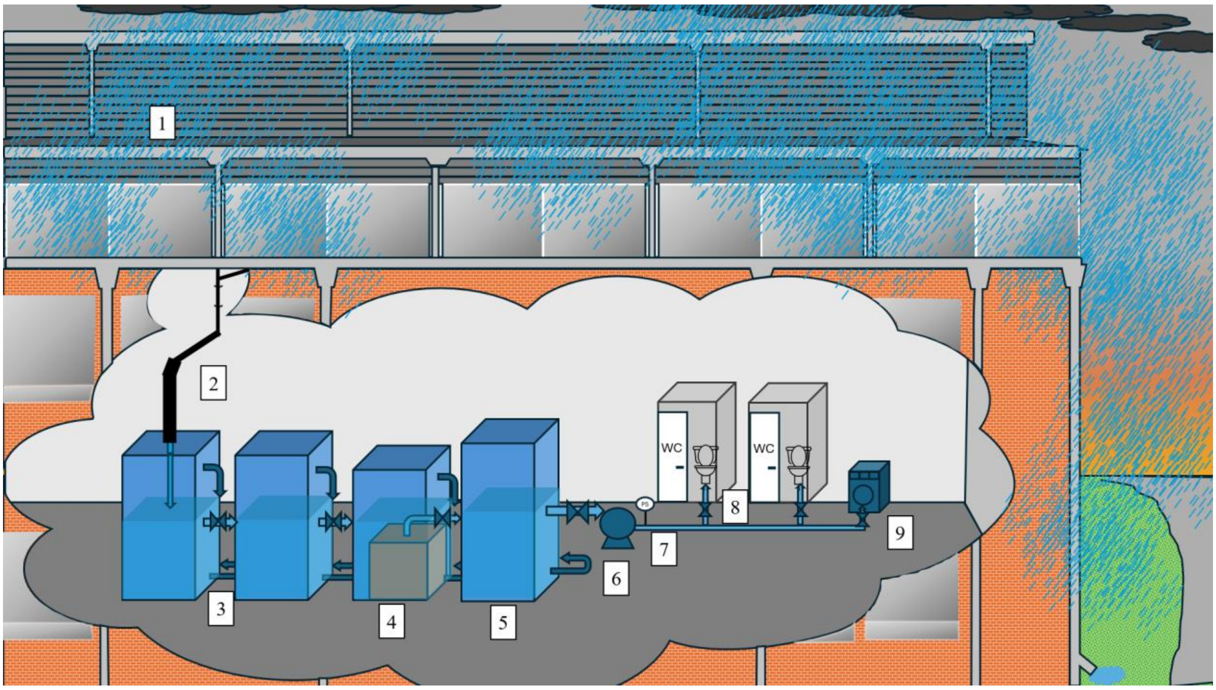

Figure 4.1. A simplified illustrated overview of the rainwater treatment setup at Kemicentrum.

1. Rooftop & Gutters
2. Indoor Pipeline
3. Collection Tank
4. Membrane Filter
5. Permeate Tank
6. Pump
7. Pressure Sensor
8. Toilets
9. Washing Machine

Figure 4.2. Overview of the pilot-scale rainwater treatment facility installed at Kemicentrum in Lund.

Rainwater is collected from the rooftop of Kemicentrum where it is drained into the gutters. The gutters are redirected into an indoor pipeline which transport the water from the roof into the membrane facility. The used rooftop area at Kemicentrum was about 240 m^2, see Figure 4.3. The runoff flows down into the first of the two 2 m^3 rainwater collection tanks. A pipe with a valve mounted halfway up the tank connects the tanks allowing free flow between the tanks.

Figure 4.3. Rain collection area on the roof of Kemicentrum. Picture drawn in Daftlogic.com's Google Maps Area Calculator.

The ceramic membrane (Cembrane SiCBlox™ FX Series) is submerged in the third tank with a tank volume of 1 m^3, see Figure 4.4 and Figure 4.5 for details about the membrane. The fourth and last tank is connected to the membranes permeate manifold on top of the membrane module. The permeate tank is connected to an automatic pump (Biltema PA 1301) which forward the permeate to two toilets and a washing machine on demand. The storage tanks and the membrane tank are equipped with overflow pipes at the top edge which is connected to the sewage. At the bottom of the tanks there are drainpipes with valves which also are connected to the sewage.

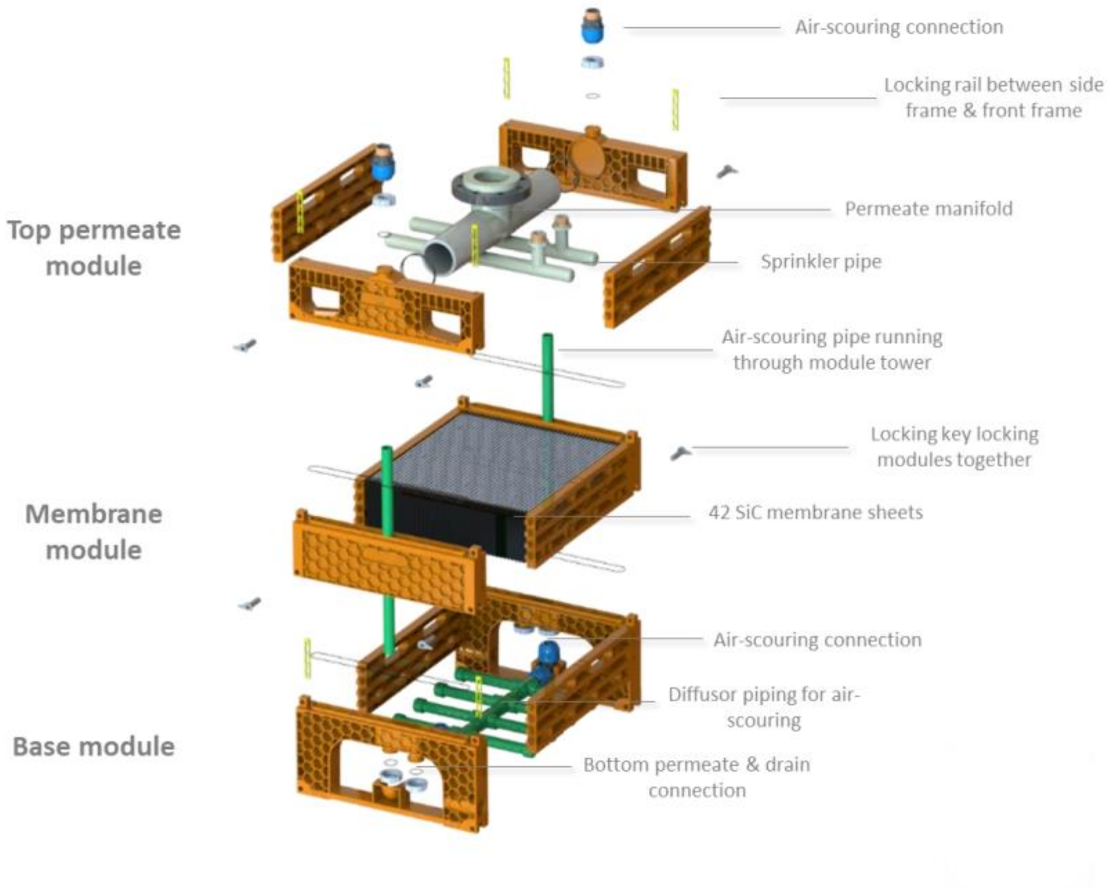

Figure 4.4. Module tower parts of the Cembrane SiCBlox™ FX Series (Cembrane A/S, n.d-b). Picture retrieved with consent from Cembrane A/S.

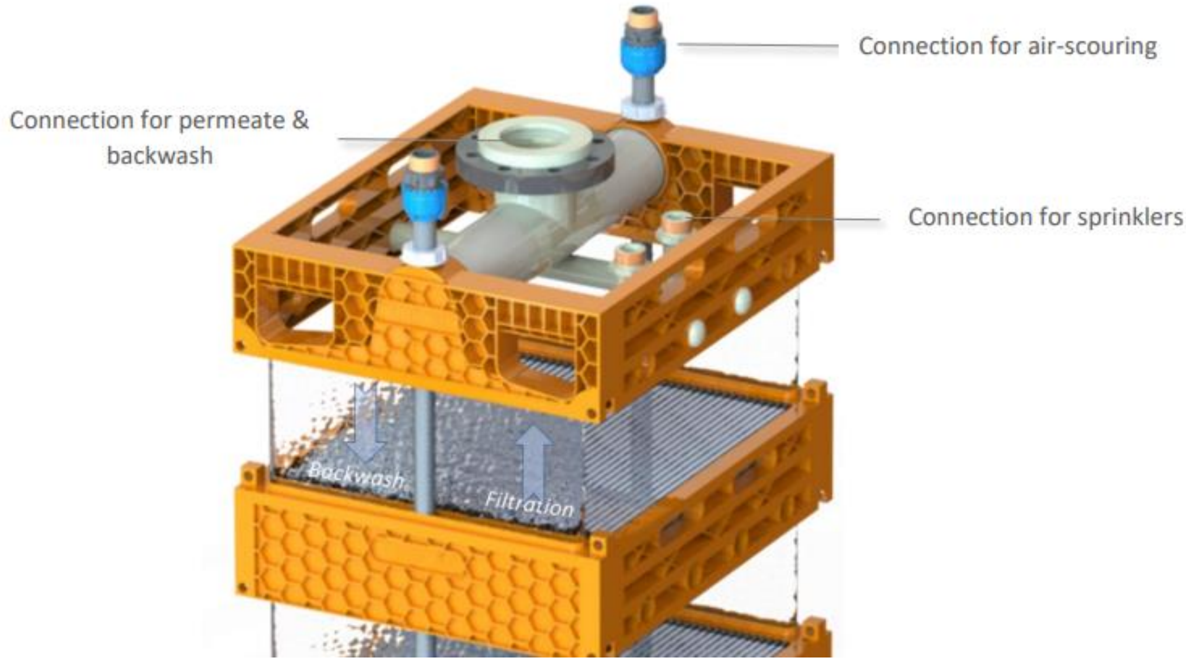

Figure 4.5. Illustration of the water flow inside the membrane module (Cembrane A/S, n.d-b). Picture retrieved with consent from Cembrane A/S.

The specifications for the membrane and pump are given in Table 4.1 and Table 4.2 respectively.

Table 4.1. Membrane module specifications (Cembrane A/S, n.d-b). Data collected by consent from Cembrane A/S.

Specifications	**Property**
Manufacturer	Cembrane A/S, Lynge, Denmark
Membrane type	Submerged Flat Sheet
Membrane material	Silicon Carbide (SiC) ceramic
Number of flat sheets per module	42 pcs
Active membrane area	6.9 m^2
Pore size	0.1 µm
Operation mode	Out-to-in filtration
Clean water permeability	>3,000 $L/m^2/h/bar$ @20°C

Table 4.2. Pump specifications (Biltema, n.d).

Specifications	**Property**
Manufacturer	Biltema
Model	PA 1301
Power	1,300 W

4.2 Analytical Methodology

The raw rainwater samples were collected from the surface of the first storage tank and from the permeate tank. The samples were collected in 1 L plastic bottles in triplicates.

4.2.1 Turbidity Measurement

Turbidity was analyzed in a turbidimeter (Hach 2100P ISO Portable turbidimeter) in accordance with APHA Method 2130 (American Public Health Association, 1992). The rainwater sample was thoroughly shaken. Before transferred into a turbidity tube the air bubbles were let to disappear. The tube was then placed in the instrument and the nephelometric turbidity unit (NTU) was read directly from the instrument. The samples was collected in triplicates and each sample was analyzed three times in the turbidimeter.

4.2.2 Total Suspended Solids Measurement

Total Suspended Solids (TSS) was measured according to the Swedish standard SS-EN 872:2005 (Swedish Institute for Standards, 2011) with VWR® Glass Fibre Filters, Grade 691, with a particle retention of 1.6 µm in an experimental setup presented in Figure 4.6. All rainwater samples were heavily shaken before the measurement to ensure no sedimentation of the suspended solids had occurred. The filter was pre-dried with a '*Blank test'* in order to measure the mass loss of the filter. The procedure is presented as follows:

Blank test

1. A 2,000 mL vacuum flask was connected to a vacuum pump.
2. A sand core filter with a rubber bung was placed on the opening of the vacuum flask.
3. A micro-glass filter (VWR® Glass Fibre Filters, Grade 691) was put on a measure scale and the weight was noted.
4. The micro-glass filter was placed on the sand core filter and a cylinder glass funnel was placed upon the filter and secured with a spring clamp.
5. Vacuum was applied and the filter was washed with 10-20 mL distilled water three times to properly seal it to the sand core filter.
6. 150 mL of distilled water was filtered.
7. Vacuum was applied until all water traces was removed. About three minutes.
8. The vacuum was turned off and the pressure was equalized before removing the filter with a flat edged tweezer and placing it in an aluminum pan.
9. The aluminum pan with the filter was placed in an oven at 105°C and dried for one hour.
10. The filter was cooled to ambient temperature in a desiccator before weighing. The filter was removed with a flat-edge tweezer and weighed without the aluminum pan.

Sample test

1. Procedure 1-5 in the *Blank test* was repeated.
2. 250 mL of sample was filtered four times. In total 1,000 mL. The filter was washed with 10-20 mL of distilled water three times between the samples to remove any dissolved solids trapped in the filter.
3. Vacuum was applied until all water traces was removed. About three minutes.
4. The vacuum was turned off and the filter was placed in the aluminum pan and dried in an oven at 105°C for one hour.
5. The dried filter was placed in a desiccator to cool to ambient temperature after drying.
6. The dried filter was weighed, without the pan, and the weight was noted.
7. The procedure was repeated on a total of three samples.

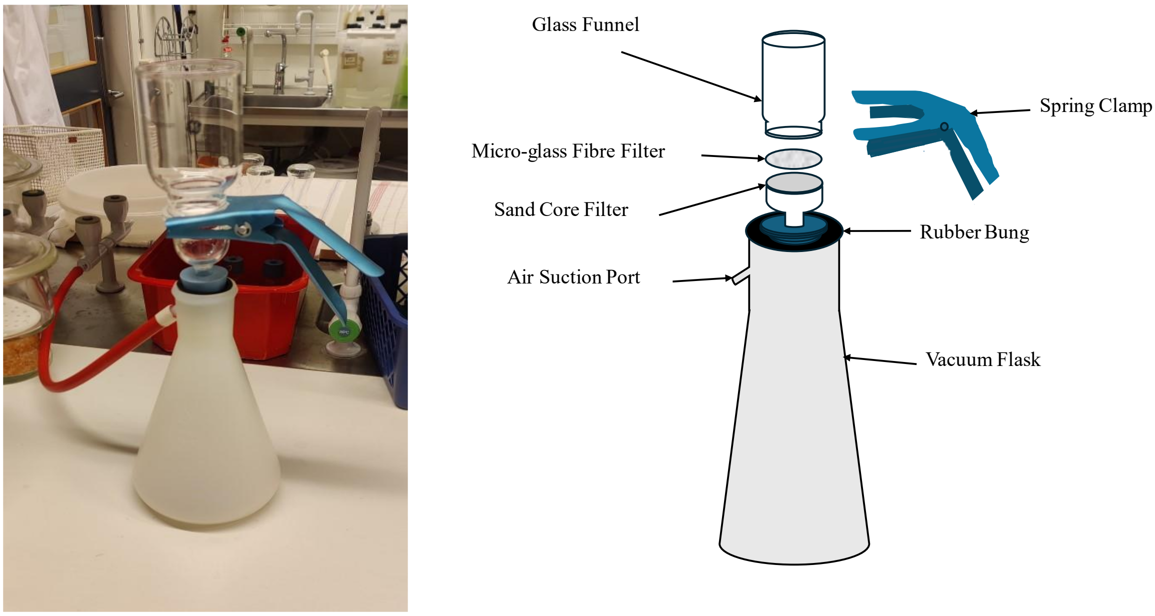

Figure 4.6. Experimental setup of vacuum flask used to filtrate water sample through a micro-glass fibre filter to measure TSS.

4.2.3 pH Measurement

The rainwater samples was analyzed with a pH-meter (Hanna Instruments 2020 Edge Hybrid Multimeter). The instrument was calibrated with buffer solutions of pH 4 and 7. The water samples was measured three times per sample where the pH-meter was washed with deionized water and whipped off with soft tissue paper in between the measurements.

4.2.4 Hydrostatic Pressure Measurements

The hydrostatic pressure of the system was obtained by filling the tank containing the submerged membrane module with tap water up to the overflow pipe. The water was let pass through the membrane until no flow of permeate was observed. The height of the water pillar removed from above the membrane was measured. The water level in the permeate tank was kept below the pipe inlet during the hydrostatic pressure measurement.

4.2.5 Volumetric Flow Measurements

In order to measure the volumetric flow, the communicating pipe between the previous storage tank and the membrane tank was closed. The membrane tank was filled to the overflow pipe and the permeate tank was empty. The valve to the permeate tank was then opened. The time it took until the driving force was equalized was clocked and the volume of the water in the permeate tank was measured. The procedure was repeated three times.

4.2.6 Flux Measurements

To obtain the flux for different water heights the membrane tank area was first measured to obtain the volume. Then with the valves closed to the connecting pipes and the membrane tank was filled with water with a hose from a tap in the tap water case and with help of a drainage pump in the rainwater case. The water level was about 5 cm below the overflow pipe. The height was chosen as it was visually easier to determine the water surface at that level as the membrane tank had a gridded wall surface. The valve into the permeate tank was then fully opened until the water level in the membrane tank had decreased by 10 cm. The time it took for the water level to decrease was clocked. Then the next 10 cm was filtered, and the procedure was repeated until no driving forces was observed. The experiment was performed three times with both tap water and rainwater.

4.2.7 Energy Measurement

The facility operate by hydrostatic pressure and does not consume electrical energy. The only exception is the automatic pump providing the toilets and the washing machine with water from the permeate tank. To measure the energy consumption the time it operates after a flush was clocked. With that information the energy usage per flush could be calculated.

4.2.8 Coliforms and Legionella Measurements

The analysis of coliforms and Legionella was planned to be analyzed by external actors but due to unforeseen events the analysis were not able to be performed.

4.3 Calculations

4.3.1 Calculation of Standard Deviation

The standard deviation is used to assess the accuracy of the laboratory analysis of the samples and was calculated with Equation 4.

$$\sigma = \sqrt{\frac{\Sigma(x_i - \mu)^2}{N}} \tag{4}$$

where:

σ = standard deviation of the measurement

x_i = each measured value

μ = the mean value of all measurements

N = number of measurements

The mean value of all measurements were calculated with Equation 5 as follows:

$$\mu = \frac{sum\ of\ all\ measurements}{number\ of\ measurements} \tag{5}$$

4.3.2 Total Suspended Solids Calculation

The suspended solids was calculated with Equation 6 as follows:

$$TSS\ (mg/L) = \frac{(A - B)}{C} \tag{6}$$

where:

A = weight of the glass-fiber filter + suspended solids

B = weight of the glass-fiber filter

C = volume of sample filtered

4.3.3 Hydrostatic Pressure Calculation

The hydrostatic pressure is calculated with the Equation 7 as follows:

$$p\ [Pa] = \rho * g * \Delta h \tag{7}$$

where:

p = hydrostatic pressure

ρ = density of water

g = gravitational acceleration

Δh = height difference of water pillar

4.3.4 Flux Calculation

The flux is calculated with the Equation 8 as follows:

$$J\ [L/m^2/h] = \frac{Q_p}{A_{membrane}} \tag{8}$$

where:

J = flux

Q_p = flow rate of permeate

$A_{membrane}$ = membrane area

The flow rate was calculated as follows:

$$Q_p\ [L/h] = \frac{A_{membrane\ tank} * \Delta water\ level}{\Delta time} \tag{9}$$

where:

$A_{membrane\ tank}$ = area of the membrane tank

$\Delta water\ level$ = difference in water level

$\Delta time$ = difference in time

4.3.5 Permeability

The permeability of the membrane is calculated by Equation 10 as follows:

$$Permeability\ [L/m^2/h/bar] = \frac{J}{\Delta P_{TMP}} \tag{10}$$

where:

J = flux

ΔP_{TMP} = trans-membrane pressure

The permeability is measured in the unit $L/m^2/h/bar$.

5 Results and Discussion

This section of this report focus on presenting and discussing the result of the water analysis, parameters relevant to the performance of the membrane module in the facility. It also presents the economy of the facility. Raw rainwater from the rooftop of Kemicentrum, tap water from the Apparatus Hall at Kemicentrum, and permeate from the facility is compared.

5.1 Rainfall During Experimental Operation

The facility is dependent on the inflow of rain, the precipitation per week from when the facility was installed, and four weeks forward is presented in Table 5.1 below. The weekly precipitation was collected from SMHI (2024b). During week 15 heavy rain was observed on the 11th and 12th of April, however the data is missing in the report from SMHI. It can be due water sensor giving bad results or being out of operation according to SMHI.

Table 5.1. Weekly precipitation from when facility installation was completed. (SMHI, 2024b).

Week	**13**	**14**	**15**	**16**
Precipitation [mm]	7.7	29.3	0*	5.3

*No reported data from 11th and 12th of April by SMHI

5.2 Water Analysis

The water analysis was performed in triplicates and the results are presented in Table 5.2 where the average values and the standard deviation of the measurements are presented. Unfortunately, the analysis of microorganisms in the rainwater were not able to be conducted and hence they are omitted from the report.

Table 5.2. Comparison of pH, turbidity and TSS in raw rainwater from the rooftop of Kemicentrum, tap water and permeate.

Parameter	**Raw Rainwater**	**Permeate**	**Tap water**
pH [-]	6.63 ± 0.012	7.30 ± 0.046	7.66 ± 0.026
Turbidity [NTU]	4 ± 1.4	1 ± 0	0 ± 0
TSS [mg/L]	< 2	< 2	< 2

It can be seen that the raw rainwater was slightly acidic compared to the tap water and the permeate rainwater which can be a result of dissolution of atmospheric gases in the rain giving acidic compounds in the presence of air as Haq (2017) reported of. The components in the water giving the acidity were retained by the membrane as the permeate had higher pH after filtration than before.

The measurement of turbidity points out that there was dissolved particles in the rainwater contributing to slight turbidity as the measured turbidity was 4 ± 1.4 NTU. According to the regulation LIVSFS 2022:12 from the Swedish Food Agency (Livsmedelsverket, 2022) drinking water has a limit of 1.5 NTU at the receiving end, by the user, which indicate that the rainwater is in need of treatment to give indication of being as clean potable water. At 4 NTU and above the water gets cloudy or turbid and less transparent (WHO, 2017), the turbidness can be diverted from suspensions in the rainwater coming from either the air or from the catchment surface

(Campisano *et al.*, 2017). The membrane was able to reduce the turbidity by 75% down to 1 NTU. That is comparable with rainwater analyzed by Kus *et al.* (2013) which had an initial rainwater turbidity of 1.5 NTU and was reduced down to 0.3 NTU with help of a gravity driven polymeric membrane with same pore size of 0.1 µm. Shiguang *et al.* (2021) reduced rooftop rainwater from 5.82 NTU down to 0.46 NTU with gravity driven flat sheet alpha-alumina membranes with 0.1 µm pore size as well. The raw rainwater from the rooftop of Kemicentrum was not visually turbid in small samples as seen in Figure 5.1, however in the storage tanks in the same figure, the water was seemingly turbid. The turbidity though can differ over time, and both increase and decrease as the contamination can vary due to winds, temperature, dry periods, seasons and traffic for instance. The water after the filtration, seen in Figure 5.2, has a clearer apperance which correspond to the reduction in turbidity.

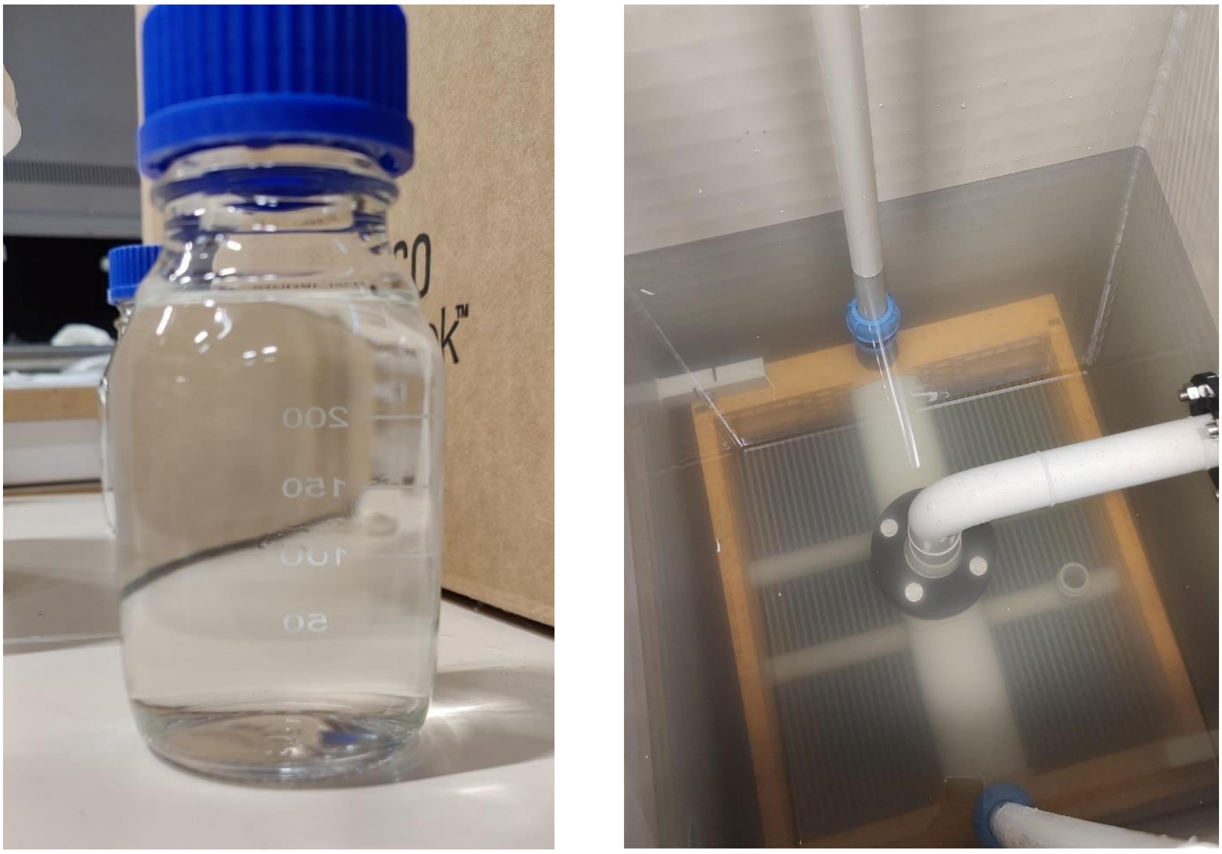

Figure 5.1. Raw rainwater sample from Kemicentrum rooftop to the left. Rainwater in the membrane tank with visible cloudiness to the right.

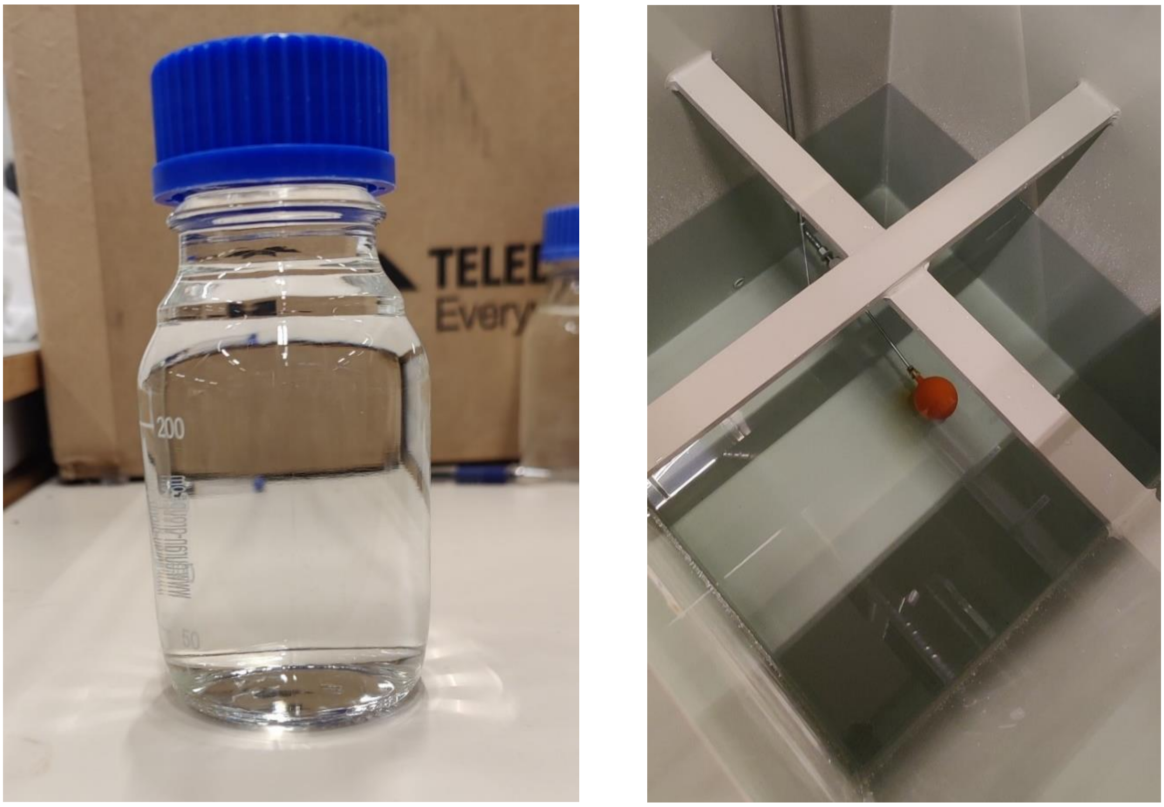

Figure 5.2. *Permeate sample to the left. Rainwater in the permeate tank to the right.*

According to the Swedish Institute for Standards SS-EN 872:2005 (Swedish Institute for Standards, 2011), TSS results lower than 2 mg/L should be displayed as ´< *2 mg/L*´. Even if the results cannot be defined more specifically, the visualization of the samples can be interpreted, see Figure 5.3 and Figure 5.4.

Figure 5.3. The micro-glass fibre filters after TSS-analysis of raw rainwater. The dark circles are the residues from the raw rainwater.

Figure 5.4. The micro-glass fibre filters after TSS-analysis of the permeate.

It can though be seen on the micro-glass fibre filters from the TSS analysis in Figure 5.3 that the raw rainwater was not clean. The solids that was retained contribute to decolorization of the filters. The mass of the solids were not sufficient to indicate above 2 mg. Therefore not much can be said about the amount of TSS in the water, however, the comparison between Figure 5.3 and Figure 5.4 indicate that the membrane are able to reduce the decolorizing compounds in the water.

The filters used in the TSS measurement had a retention, or pore size, of 1.6 µm so that the dissolved solids possibly has passed the glass fibre filter, unless it possibly was too little of solids in the raw rainwater. A larger sample volume could be used to obtain a greater suspended solids mass, however according to the Swedish Institute for Standards (2011) the limit of volume per sample for the TSS method is 1,000 mL which was the volume used in the analysis. Analysis with other filters with smaller pores could possibly show another result and preferably a filter with pore size close to the membranes 0.1 µm should be used to define the TSS. Unfortunately, no filters with smaller pore sizes were available. The result though show that the discoloration of the water is reduced by the membranes.

5.3 Membrane Performance

The results of the membrane performance test are found in Table 5.3 where the average values of the parameters from the experiments are presented. In Figure 5.5 and Figure 5.6 the flux and permeability are presented as functions of the hydrostatic pressure in the membrane tank.

Table 5.3. Experimental results of flux, permeate flow and permeability with tap water and rainwater.

Parameter	**Tap water**	**Rainwater**
Flux [L/m^2/h]	270 ± 6	205 ± 30
Permeability [L/m^2/h/bar]	6,850 ± 155	5,020 ± 750

The system is gravity driven hence the driving force is coming from the pressure from the water pillar above the permeate manifold. The permeate flows from the interior of the membrane sheets up to a permeate manifold and end up in the permeate tank. The manifold is located 1 m above the bottom of the tank and the overflow pipe is located 1.7 m above the bottom. The maximum hydrostatic pressure is obtained from the 70 cm water pillar above the manifold and with water level in the permeate tank below the inlet. The corresponding hydrostatic pressure was calculated to be 68 mbar with an assumed water density of 1,000 kg/m^3 and assumed gravitational acceleration of 9.81 m/s^2.

The pressure was found decreasing as the water passes through the membrane and subsequently as the water level decreases. The pressure was found decreasing linearly with the decreasing water level which also proportionally decreases the flux as illustrated in Figure 5.5 and Figure 5.6.

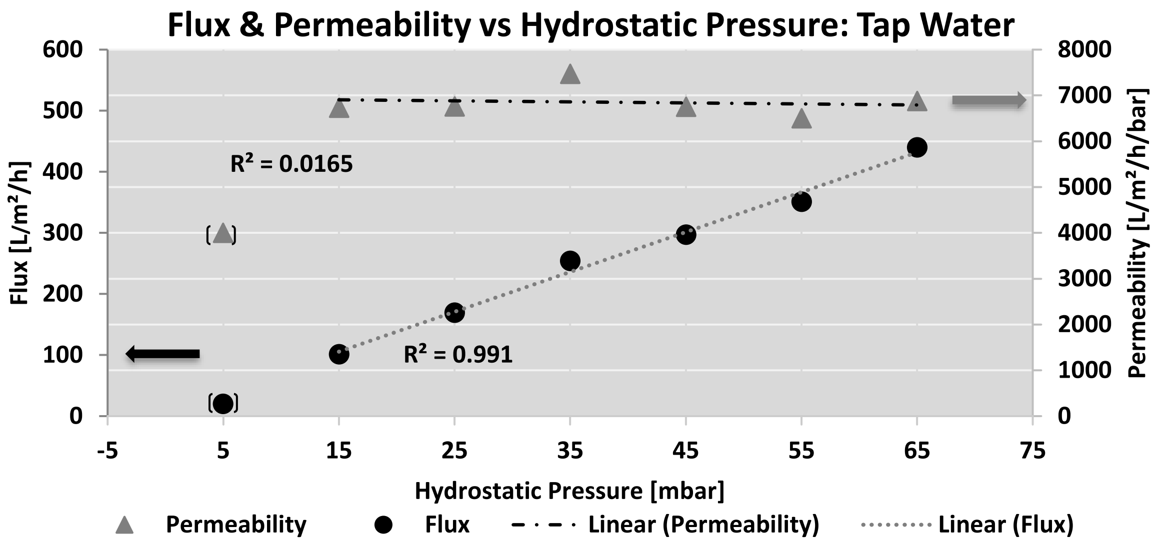

Figure 5.5. Tap water flux (y1-axis) and permeability of the membrane module (y2-axis) as a function of the hydrostatic pressure (x-axis) in the membrane tank. The black dots (●) represent the flux and are connected to the y1-axis on the left-hand side. The grey triangles (▲) are showing the permeability connected to the y2-axis on the right-hand side. The grey dotted line (…) is the trendline for the flux with corresponding and coefficients of determination. The black dash dotted line (-.-) is the trendline for the permeate with corresponding coefficients of determination. The arrows indicate what axis the values correspond to. The values within brackets does not contribute to the coefficients of determination.

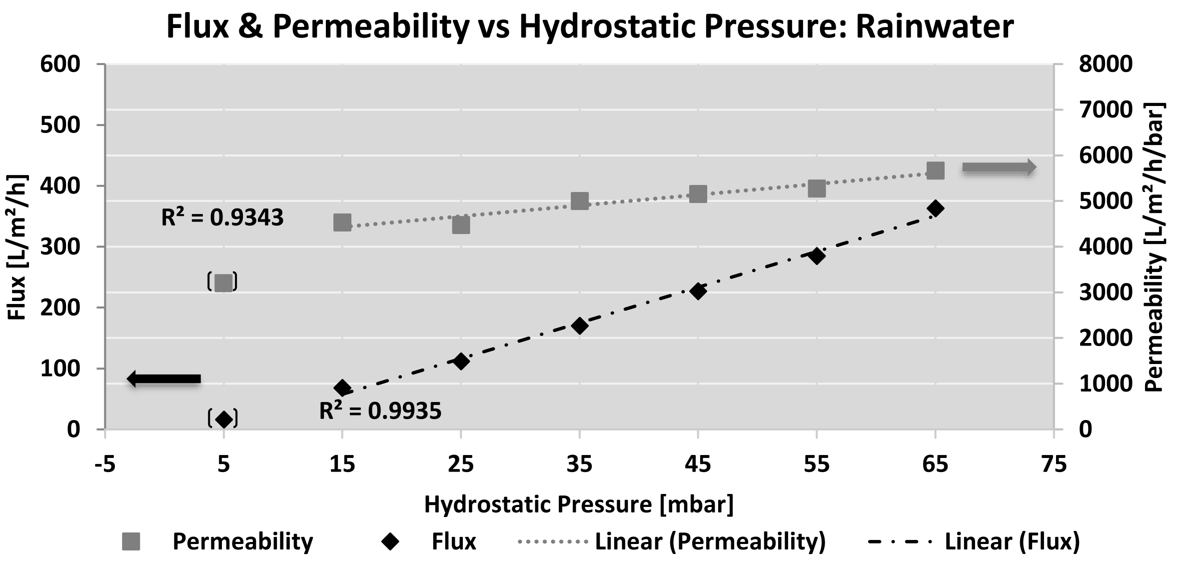

Figure 5.6. Rainwater flux (y1-axis) and permeability of the membrane module (y2-axis) as a function of the hydrostatic pressure (x-axis) in the membrane tank. The black diamonds (♦) represent the flux and are connected to the y1-axis on the left-hand side. The grey squares (■) are showing the permeability connected to the y2-axis on the right-hand side. The grey dotted line (…) is the trendline for the flux with coefficients of determination. The black dash dotted line (-.-) is the trendline for the permeate with corresponding coefficients of determination. The arrows indicate what axis the values correspond to. The values within brackets does not contribute to the coefficients of determination.

The measurement at 5 mbar in the figures, inside brackets, are measurement where the permeate manifold were not covered in water. Hypothetically, the hydrostatic pressure disappears when the water level is below the top of the manifold as it is point zero. However, it was observed that permeate were still flowing but the time to reduce the water level 10 cm was markedly longer and thus the flux was vastly reduced in comparison to the other measurements. Thus, it was not representative for the measurement series and was not included in the linear regression or calculated averages. Nonetheless, the flux obtained in that measurement was on average 20 ± 0.5 L/m^2/h with tap water and 16 ± 1 L/m^2/h with rainwater. It showed that it is possible to treat the water at a pressure of 5 mbar and below. The effect from not having the permeate manifold covered in water is suggested to be further researched.

The observed average tap water flux was 270 ± 6 L/m^2/h and the tap water permeability was 6,850 ± 155 L/m^2/h/bar. For the rainwater the flux was lower, and the obtained average flux was 205 ± 30 L/m^2/h, while the permeability was 5,020 ± 750 L/m^2/h/bar. The difference in flux between the tap water and rainwater is likely due to filtration resistance caused by fouling on the surface of the membrane when using rainwater, which lower the performance of the membrane. Shiguang *et al.* (2021) found after 60 days of rainwater filtration without cleaning in a ceramic gravity driven membrane that the flux stabilized between 22-45 L/m^2/h with a constant water head of 2 m in lab-scale. It gives an indication of the direction the performance heads towards. In comparison, the standard deviation was greater on the rainwater measurements which possibly could have been less if the membranes were cleaned in between the measurement. Instead, it could have been a build-up of fouling which contributes to larger deviation in the flux measurements.

The permeability was observed decreasing linearly with the decreasing hydrostatic pressure when filtering rainwater. While it in the tap water case did not behave similarly and the coefficient of determination shows that the pattern is not linear. The permeability in the tap water case goes up and down at different pressures. No similar research have been found regarding this behavior. A possible explanation given by Senior Project Manager at Cembrane A/S, Wolfgang Krämer (2024) is that the hardness of the water can cause a concentration gradient close to the membrane surface. However, more studies need to be done to explain the behavior.

Currently the use of ceramic membranes to treat rainwater is rare and thus few comparisons and explanations of the behavior can be conducted.

5.4 Economy

The capital expenditure for the facility was in total 350,000 SEK. The facility operate on hydrostatic pressure with only operational cost connected to the pump supplying the toilets with filtered rainwater. No power transmitter was connected to the pump so the energy consumption could not be determined. According to the pump manual, the pump has a maximum power of 1,300 W which can provide a 40-50 m water head at volumetric flows below 1 m^3/h (Biltema Nordic Services AB, 2016). The water head difference between the pump and the toilet cistern is about 50 cm. The energy consumption is presumably low.

It is assumed that the technical lifespan of the facility is 10 years, and thus a technical depreciation time of 10 years is assumed. It is further assumed that the toilets are only used during weekdays during an academic year during which students, researchers and other staff are at Kemicentrum. The academic year is around 200 weekdays. Furthermore, by using rainwater Kemicentrum saves the municipal water fee of 11.94 SEK/m^3 (VA SYD, 2024) when flushing with rainwater. It is also assumed that the toilets at Kemicentrum consumes 6 L per flush (NSVA, n.d). The corresponding calculated cost per cubic meter of treated rainwater in different cases is presented in Table 5.4. In the tax attachment from VA SYD (2024) there is also more cost regarding the use of drinking water that Kemicentrum can save if rainwater is utilized. However, the exact amount of what Kemicentrum pays per cubic meter drinking water was not received from the landlord within the time frame of this project.

Overall, the facility offers an uncomplicated and energy efficient approach to reuse rainwater and reduce the consumption of potable water. The facility demonstrate what Pronk *et al.* (2019) found, that gravity driven membrane filtration offers a cheap filtration due low operational pressures and low requirement of chemicals. The corresponding consumption cost for filtered rainwater in the pilot facility is much higher than consuming drinking water. This is largely due to the capital expenditure of the facility. With larger implementation the corresponding cost per cubic meter rainwater will be vastly reduced as will be seen in Chapter 6, later on in this report.

Table 5.4. Corresponding water price based on the number of flushes per day, 10 years technical depreciation time and 6 L water requirement per flush. One cubic meter of potable water cost 11.94 SEK/m^3 (VA SYD, 2024).

Number of flushes per day	**Annual Water Consumption [m^3/year]**	**Water Fee Savings [SEK/year]**	**Cost [SEK/m^3]**
20	24	290	1,400
30	36	430	1,000
40	48	580	720
50	60	720	580

5.5 Improvements

A suggestion for improvement to the pilot-scale facility is to have an additional pipe to be able to redirect the rainwater directly into the membrane tank. As per now the rainwater is directed into the far most left collection tank in Figure 5.7. The additional pipe can be used in situations when the water level in the membrane tank is low and permeate is running low. By redirecting the water into the membrane tank directly the dead volume in the collection tank can be bypassed. The major drawback with rainwater directly into the membrane tank is the contamination from the roof that would accumulate in the membrane tank. Today's setup enables particles to sediment in the collection tanks before membrane filtration. By having direct filtration, the accumulation of contamination will be greater in comparison. This would require drainage of the membrane tank more often to minimize fouling on the membrane sheets and to remove sedimentation from the bottom of the tank. Another disadvantage is that cleaning or maintenance have to take place during dry periods as the pipelines from the gutters lacks alternative pathways. Which could be solved with additional pipes and valves on the pipeline in order to redirect it to, for instance, the collection tanks.

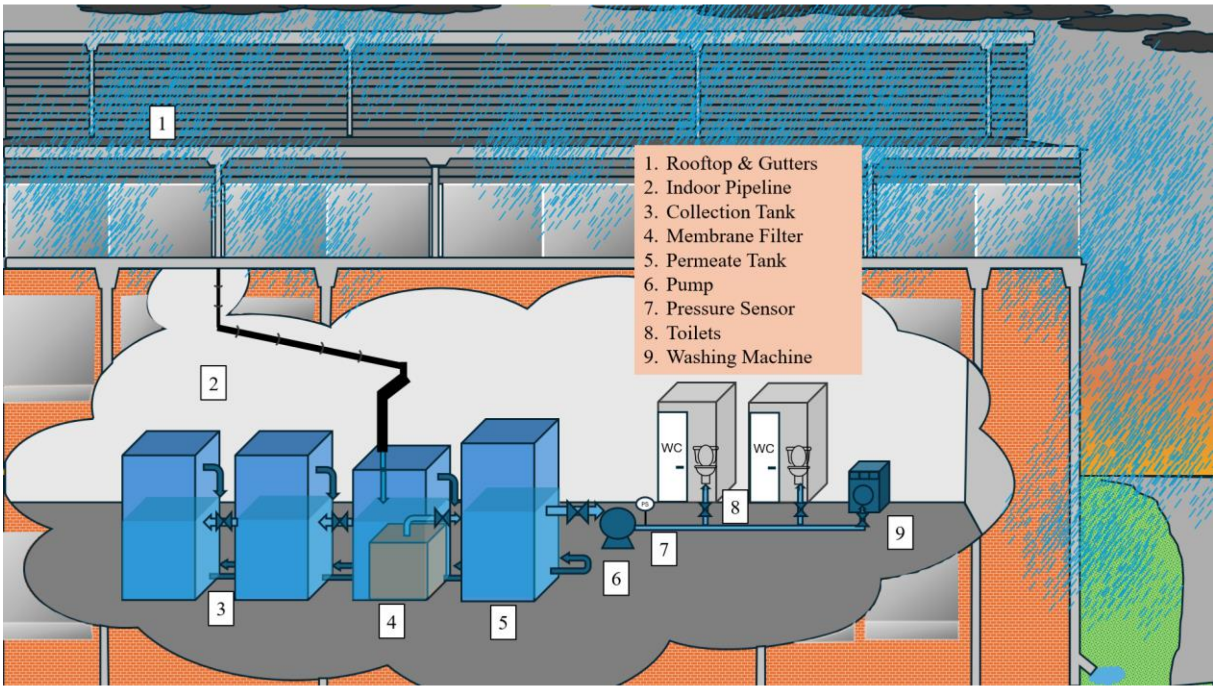

Figure 5.7. Suggestion for improvement to the pilot-scale facility at Kemicentrum. The indoor pipeline is moved from the tank to the far left to the membrane tank in the original set-up.

Moreover, the membrane module has pre-installed air scoring connections which could be connected to an air stream to prolong the time the retentate can remain in the membrane tank. Also, connections for sprinklers are pre-installed and can be used if necessary. Preferably filtered rainwater should be considered for backwashing instead of tap water. In that case a pump would be necessary to install or add a pipe and valve from the current pump into the membrane module.

The drawback of the design of the water tanks are the placement of the communicating pipes. The pipes are located 1 m from the bottom which creates a dead volume. Only water levels above 1 m results in filling of the adjacent tank. Lowering the pipes would decrease the dead volume. Though, it should not be placed at the very bottom. The design allows particles to settle to the bottom and thus the sedimentation is not transferred between the tanks.

6 Scale Up Case

Kemicentrum is a building used by Lunds University housing offices, lecture halls and laboratories for students, scientists, and professors among others. On average, 1,000 people are circulating the premises daily (Lindblom, 2024).

This chapter will present the supply and demand of water for Kemicentrum and a suggestion of an upscaled rainwater collection system for the entire Kemicentrum based on the pilot-scale facility.

6.1 Rainwater Supply

The water supply is dependent on the volume of rain, the catchment area and runoff coefficient and can be calculated through the 'Supply-Side Approach' (Haq, 2017) which is presented in Equation 11.

$$Supply = Catchment\ Area * Rainfall * Runoff\ Coeffiecient \tag{11}$$

6.1.1 Rainfall

Historical precipitation, or rainfall, can be used to estimate the rainwater supply. The data used in the calculations are collected from SMHI's climate database PTHBV. PTHBV contains data from SMHI's meteorological stations and are interpolated into the database grid squares through a method known as 'optimal interpolation' (SMHI, 2022). This data has been corrected for measurement losses due wind at the measuring station. The method also consider if the precipitation is in the form of snow or rain. The data was downloaded from the chosen grid with coordinates 62.309, 16.030 (coordinate system WGS 84) corresponding to the Kemicentrum's position. The collected data is presented in detail in Appendix A, in Table A.1. On average it rains 64 mm per month or 780 mm annually based on the monthly precipitation from January 2002 to December 2023 (SMHI, 2024a).

Figure 6.1 below presents the maximum, average, and minimum precipitation of each month in Lund during the period 2002 to 2023. The diagram illustrate both the potential in collecting rainwater and the importance of having redundancy in doing so. In periods with much rain, allocated during fall and winter, one want to store the excess water to be able to handle periods with low volumes of precipitation, for instance during April and May.

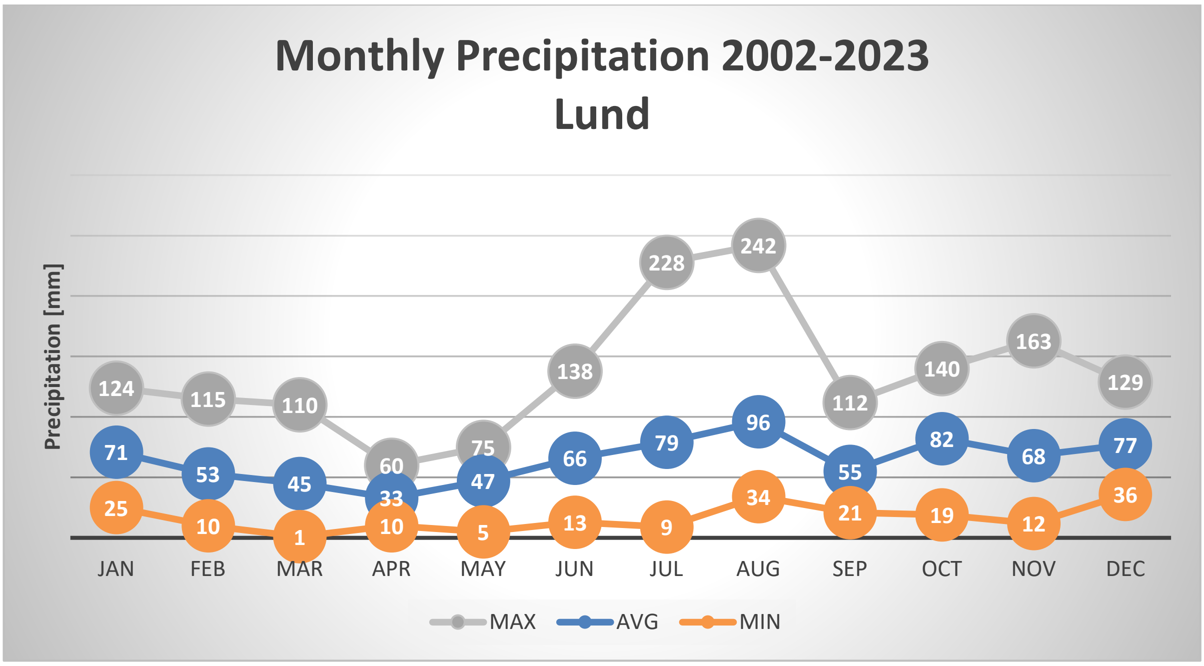

Figure 6.1. Monthly precipitation per month in Lund, Sweden, based on the rainfall statistics from the years 2002 to 2023 (SMHI, 2024a). Each color represent maximum measured precipitation, average and minimum measured precipitation per month. April is the month with the least precipitation statistically whilst August has the most precipitation.

6.1.2 Potential Rainwater Catchment Area

Besides the requirement of rain, there is also a requirement of a collecting site. The size of the catchment area greatly determines the collectable volume. Kemicentrum has in total approximately 20,000 m^2 roof area and approximately 9,000 m^2 parking surface corresponding to the highlighted areas in Figure 6.2. Rain collected from 29,000 m^2 would correspond to 29 m^3 per millimeter rain fallen. However, that is more than sufficient.

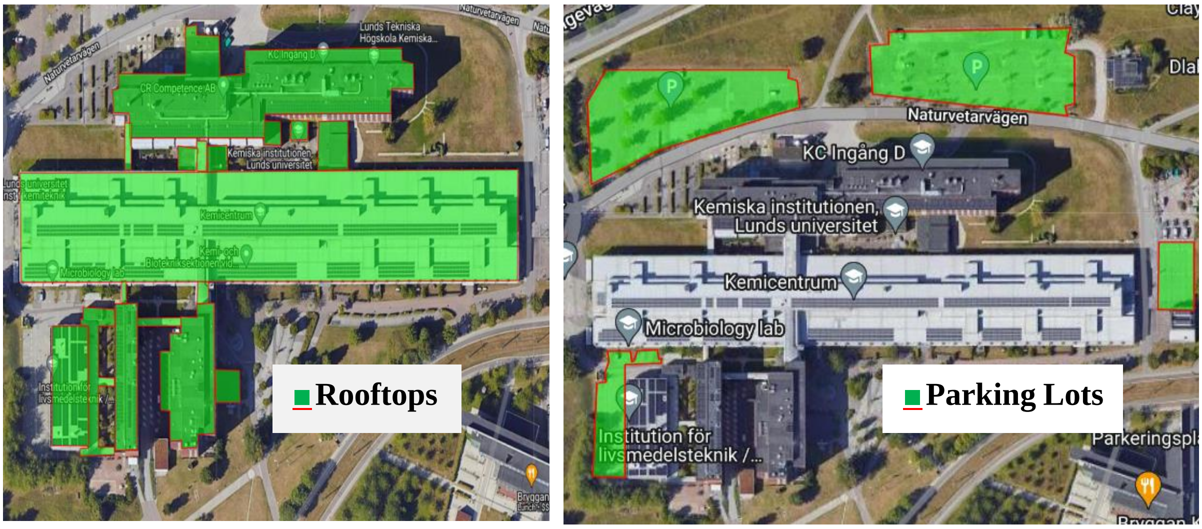

Figure 6.2. The total potentially available surface for rainwater catchment on the Kemicentrum's premises. The areas are marked green. To the left, rooftop surfaces. To the right, parking lot surfaces. Picture drawn in Daftlogic.com's Google Maps Area Calculator.

In Figure 6.3, a proposal of catchment surfaces is drawn. The marked area correspond to approximately 10,000 m^2 and is based on Kemicentrum's water demand which will be further presented below.

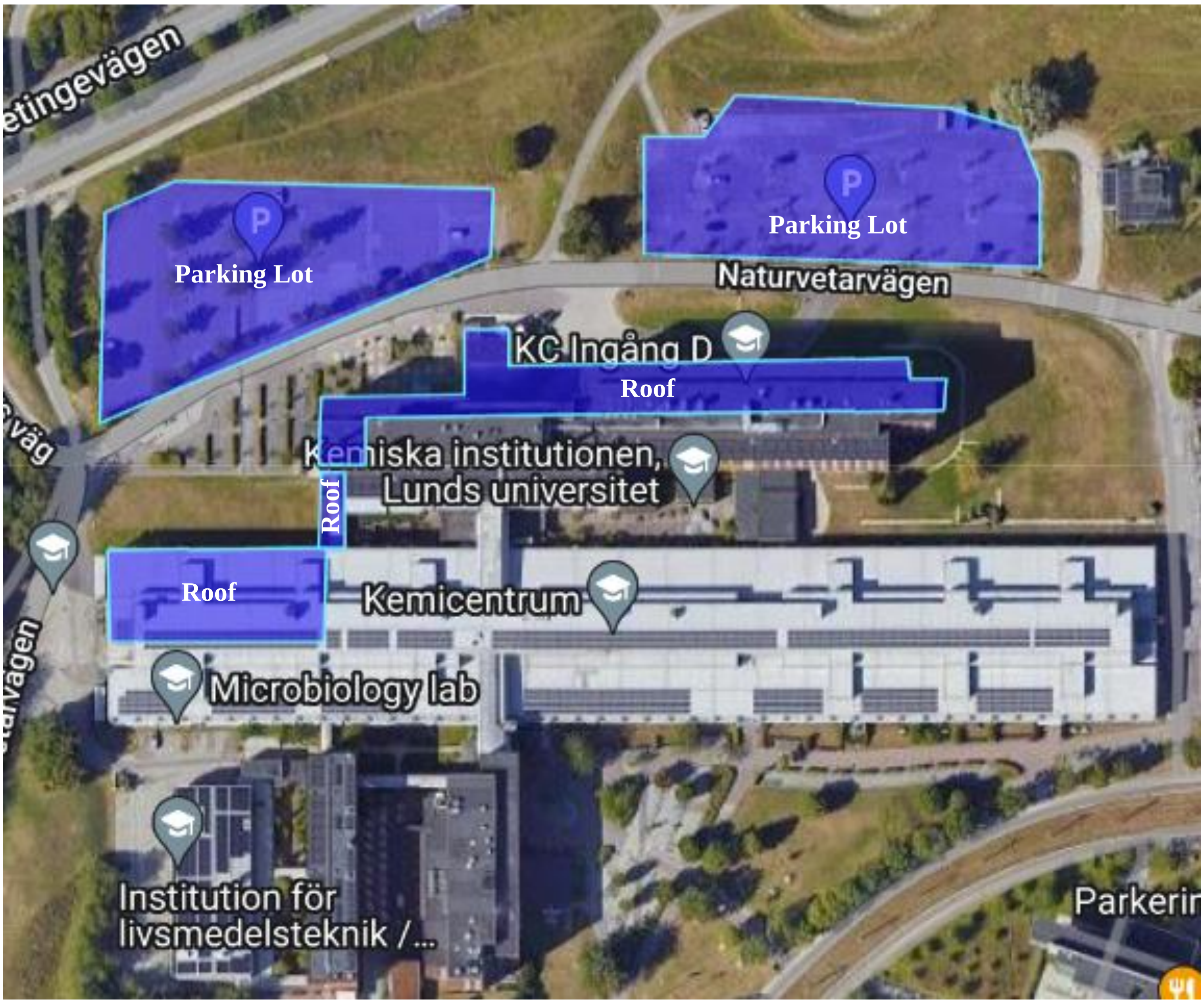

Figure 6.3. Catchment area suggested to be used for 10,000 m^2 marked in blue. Areas marked 'Parking Lot' corresponds to 6,300 m^2 and the areas marked 'Roof' corresponds to 3,700 m^2. Picture drawn in Daftlogic.com's Google Maps Area Calculator Tool.

6.1.3 Runoff Coefficient of Surfaces

The runoff coefficient describes the ratio between the drained rain and the total volume of precipitation. For rooftops the coefficient equals 0.9 and asphalt surfaces it is 0.8 according to P110 Svenskt Vatten (2016).

6.1.4 Calculated Potential Rainwater Supply

1 mm rain corresponds to 1 L/m^2 meaning Kemicentrum has potential of collecting 1,150 m^3 roof runoff from the entire roof per month. From the parking lots in total 460 m^3 of asphalt runoff can be collected per month.

In the scenario in Figure 6.3, the highlighted rooftop surface stretches to 3,700 m^2 and the parking surface corresponds to 6,300 m^2. Subsequently, 320 m^3 runoff from the parking lot and 210 m^3 runoff from the roof can be potentially collected with the runoff coefficients considered.

In total, the supply could accumulate to 530 m^3 per month based on an average precipitation of 64 mm rain per month corresponding to about 6,300 m^3 per year.

6.2 Water Demand

According to Svenskt Vatten (2017), a person on average use 30 L of potable water to toilet visits daily. Each flush uses 3-6 L of water depending on the manufacturer (NSVA, n.d), which corresponds to around 5-8 visits a day. Approximately each person visit the toilet at work 2 times during a workday, corresponding to 8-12 L of flushed water. For this case, the daily consumption is assumed to be 12 L per person, corresponding to the determined value for office areas according to Rattenbury (2020). Besides toilet flushing, rainwater could be utilized in washing machines.

6.2.1 Toilet Flushing Water Demand

As mentioned in the introduction to Chapter 6 around 1,000 people are circulating Kemicentrum daily (Lindblom, 2024). Thus, with the value from Rattenbury (2020) above, the daily toilet flushing consumption is calculated to be 12 m^3.

6.2.2 Washing Water Demand

Kemicentrum has three washing machines used by the cleaning staff. The machines and their water consumption is compiled in Table 6.1. It is estimated that the washing machines are used once a day. Their joint demand corresponds to nearly 250 L of water on a daily basis.

Table 6.1. The water consumption for each washing machine used by cleaning staff at Kemicentrum. The consumption regards full machines wash at 60°C (Alfvegren, 2024) (Electrolux).

Manufacturer	Machine	Water Consumption
Electrolux	W555H	53 L/wash
	W575H	62 L/wash
	W3130H	132 L/wash

6.2.3 Total Water Demand

The estimated total demand on a daily basis rounds up to 13 m^3. At Lund University the academical year spans around 200 days (Lunds Tekniska Högskola, 2024), during which the facilities utilizes water resources the most as it is when students in combination with researchers and professors are at Kemicentrum. Multiplying the number of days with the daily demand, the yearly demand estimate lands on 2,600 m^3 which correspond on a monthly basis to roughly 220 m^3.

6.2.4 Savings

Based on VA SYD current taxation attachment where the variable charge of delivering potable water is 11.94 SEK/m^3 (VA SYD, 2024), the annual operating expenses savings could add up to around 31,000 SEK. More savings could possibly be done as the taxation also includes fixed charges depending on the size of the building and annual fees which has not been included in the calculation as the information was not available and could not be received during the time frame of this project.

6.3 Rainwater Collection and Membrane Facility

The dimensions of the rainwater collection and membrane facility should be able to first and foremost supply the demand, and secondly be able to store water to cope with periods of precipitation scarcity.

6.3.1 Placement of Collection Tank and Membrane Module

The size and location of the collection tank or tanks are important factors to consider. Preferably the collection tanks should be placed indoors for accessibility and maintenance, but due to the size, it is more suitable to place outdoors. A placement upon the roof is not to recommend as it contribute to large loads and could negatively impact the supporting structure (Haq, 2017). A better suggestion is underground placement, which is an advantageous alternative for a couple of reasons. As per Haq (2017), it decrease the availability of sunlight which limits microbial growth. Further, it is protected from weather conditions and saves space on the premises. Underground placement do come with disadvantages such as the requirement of excavation which in turn requires a location suitable for the tank. Furthermore, the tank becomes less accessible for maintenance and the system would require suction from the tank into the membrane facility which cannot be placed underground. The facility cannot be operated in a gravity-driven manner which means increasing energy costs compared to the pilot-scale facility. To ease and decrease the need for maintenance of the collection tank a vortex chamber could also be installed prior the collection tank. The vortex chamber acts as a sedimentation tank and thus as a pre-treatment to the water, minimizing fouling on the modules.

Suggestions for placement of an excavated collection tank at Kemicentrum are two locations. The first location is on a green surface and the second location is on one of the parking surfaces, see Figure 6.4 for visualization of the individual suggestions. The placement is not limited to these two sites; however, they are two suitable locations to fit the collection tank. Placing the tank on the parking lot requires deeper excavation as the load will be greater compared to the green surface. A tank placed on the parking lot has to be more robust and thick to withstand the load from the asphalt and cars (Larsson, 2024).

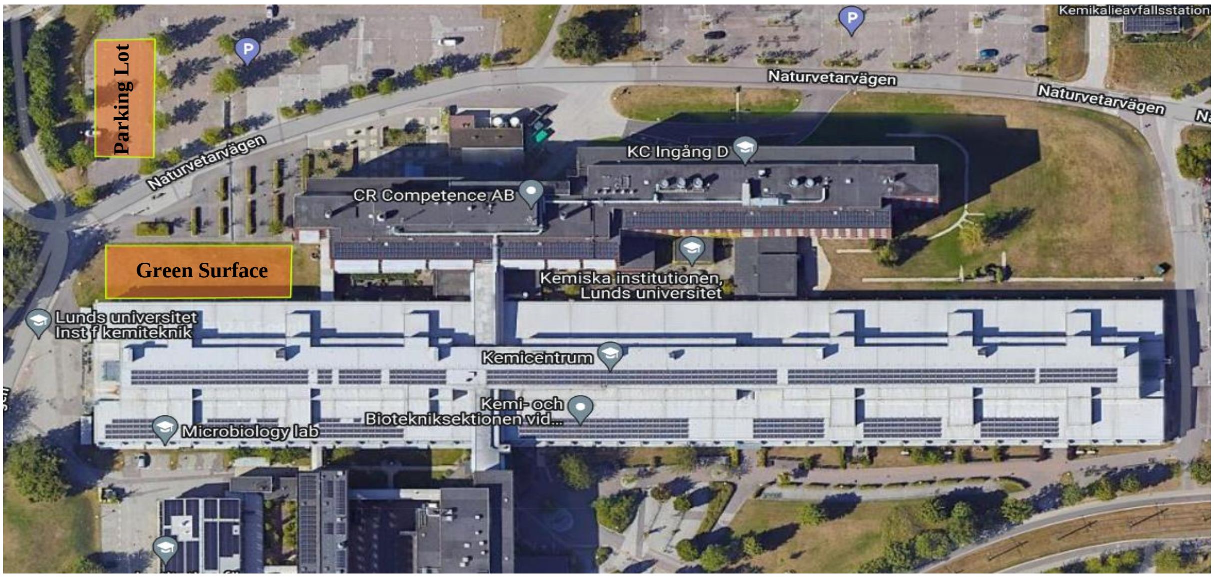

Figure 6.4. Suggested placement of the excavated collection tanks at Kemicentrum's premises. The orange marked areas represent individual suggestions. The lower is on a green surface while the upper is on a parking lot. Picture drawn in Daftlogic.com's Google Maps Area Calculator Tool.

In order to minimize the energy cost, the module should be placed close to the collection tank to minimize lengthy piping and large suction power. As the tank is suggested to be buried under soil or asphalt the facility has to be placed outdoors. The membranes, automatic cleaning-in-place system, pumps and storage tank for the permeate could be fitted and operated inside an insulated container if needed (Christensen, 2024). However, a room indoors would be preferable.

6.3.2 Tank Size

The size of the tanks is dimensioned by calculating the collectable rain based on the historical precipitation and subtracting the water demand and basing the size by the excess water. The tank is dimensioned to store approximately 10 days of consumption, corresponding to 120 m^3. In Table 6.2, one can see the tank options to achieve 120 m^3 gathered from Uponor Infra AB and the tanks considered are cylindrical tanks as in Figure 6.5 (Larsson, 2024).

Table 6.2. Diameter, length of cylindrical collection tank for a volume of 120 m^3 from Uponor Infra AB (Larsson, 2024).

Tank Diameter [mm]	Tank Length [m]
2,000	38.2
2,400	26.5
3,000	17.0
3,500	12.5

Figure 6.5. Example of Uponor Infra AB's cylindrical tanks. Provided with consent from Uponor Infra AB (Larsson, 2024).

6.3.3 Cost of Rainwater Harvesting and Membrane Facility

The dimensioning of the membrane facility assumes that people only are present in the building for a maximum of 12 hours per day. In order to meet the daily demand of 13 m^3 water for washing and toilet flushes a filtration rate of 1.1 m^3/h would be required. One module of membrane corresponds to a filtration area of 6.9 m^2 which would require a flux of 159 $L/m^2/h$. As the collection tank is proposed to be underground, the facility cannot be operated in the gravity driven manner as in the pilot scale. As such, the system will require pumping to obtain pressure instead of hydrostatic pressure. To keep the energy usage low the membrane facility is suggested to be operated with as low flux as obtainable. As shown in the pilot scale facility, the membrane observably could get a flux of nearly 20 $L/m^2/h$ at pressure as low as 5 mbar. Flux at 20 $L/m^2/h$ needs a total of 8 modules of SiCBlox^{TM} FX series to acquire the filtration rate of 1.1 m^3/h for 12 hours operation per day. The total membrane area then accumulates to 55.2 m^2. The capital cost of the modules is 1,050,000 SEK, an additional 108,000 SEK for an automatic CIP unit, and 18,000 SEK for the pump (Christensen, 2024).

There is a choice of having operation 24 hours per day which would require a slower filtration rate and thus smaller flux or less membrane area. For many reason only operating half a day can be positive. It reduces energy consumption as it does not have to operate continuously. It prolongs the equipment's lifespan as it reduces the wear and tear of pumps and membrane. By not requiring continuous operation the system gains more flexibility if the demands increases. Furthermore, it would be easier to perform maintenance on the facility as well as give room for optimizing the process on hours at which the facility is out of operation.

The collection tank costs different depending on whether it is placed on the green surface or on the parking lot. That is due to the weight of the material that will be on top of the tank. Heavy traffic or parking requires a greater bearing in the tank which increase the price. In Table 6.3, the estimated price of the tank alternative are presented. All alternatives are for a tank volume of 120 m^3 however the diameter and length varies. The prices are provided by Uponor Infra AB and the price of the collection tank include surcharge for wholesaler and entrepreneurs provided but exclude installation and shipping (Larsson, 2024).

Table 6.3. Cost estimations for placing an underground tank in different sizes on a green surface or a parking lot.

Tank Diameter [mm]	**Tank Length [m]**	**Tank Volume [m^3]**	**Estimate Price [SEK] Green Surface / Parking Lot**	**Specific Price [SEK/m^3]**
2,000	38.2	120	396,000 / 558,000	3,300 / 4,650
2,400	26.5	120	396,000 / 558,000	3,300 / 4,650
3,000	17.0	120	396,000 / 558,000	3,300 / 4,650
3,500	12.5	120	396,000 / 558,000	3,300 / 4,650

The estimated price of a vortex chamber with sedimentation capacity of 550 L is 154,000 SEK according to Uponor Infra AB. An example of a vortex chamber is presented in Figure 6.6. The tanks are cylinder shaped and it is the stiffness in the ring bearing of the pipe that determines the cost.

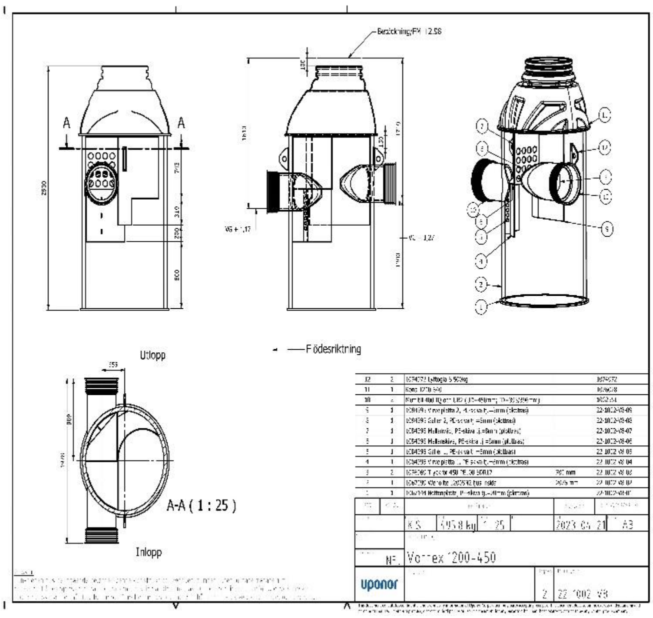

Figure 6.6. Example of Uponor Infra AB's vortex chamber. Provided with consent from Uponor Infra AB (Larsson, 2024).

The total entrepreneur costs for the membrane facility is presented in Table 6.4 and is summarized to 5.3 MSEK. The cost is calculated on the most expensive installation which is the parking lot scenario. The calculus includes excavation and piping, installation of the membrane facility indoor and connection to the water distribution system inside Kemicentrum. A more detailed list of the cost can be found in Table D.1 in Appendix D. In addition to the stated expenses, the owner of the premises will have expenses for project management which is not included in this calculation. The operating cost for the facility will be electricity and maintenance. The cost of those have not been defined in this thesis.

Table 6.4. Summary of investment costs for the membrane facility.

Object	Cost [SEK]	Comment
Machine Parts	2,368,000	
Ground and Concrete Work	603,000	
Construction	500,000	
Heat, Plumbing and Ventilation	450,000	
Electricity and Automation	700,000	
Total Costs	4,621,000	
Unpredictable	693,150	15% of total costs
Total Investment Cost	5,314,150	

The membrane has a life span of > 20 years (Cembrane A/S, n.d-a) and the collection tank has a life expectancy of at least 25 years (Uponor Infra AB, n.d). With an estimated technical depreciation time of 20 years and the estimated total expenditure for the facility each cubic meter of water would correspond to an estimated cost of 90 SEK/m^3. The cost will vary depending on the water consumption and the depreciation time. In

Table 6.5 the corresponding cost per cubic meter by different depreciation times is presented.

The cost per cubic meter is higher than the municipal water fee per cubic meter but besides reducing potable water use, the facility has potential to relieve the sewage system during heavy rains. Potentially reducing overflooding and save costs for the municipality and water treatment plants which do not have to take care of the water masses.

Table 6.5. Technical depreciation time and the corresponding cost per cubic meter water consumed based on a total capital expense of 5.3 MSEK, the annual depreciation with savings subtracted and divided by annual rainwater consumption.

Technical Depreciation Time [Years]	Corresponding cost per m^3 filtered rainwater [SEK/m^3]
10	190
15	125
20	90
25	70
30	55

In Table 6.6 a comparison between existing facility and the suggested facility are presented. It can be seen that Kemicentrum is dimensioned to consume more rainwater than Celsiushuset and Citypassagen due to more people and larger number of toilets. The collection tank in Celsiushuset is 50% larger than the proposed at Kemicentrum while Citypassagen is 50% smaller. The investment cost for the facility in Celsiushuset in Uppsala costed about 0.8 MSEK (Holm and Schulte-Herbrüggen, 2021) and Citypassagen in Örebro costed about 1.2 MSEK (Jephson and Kristiansson, 2023). The facility proposed for Kemicentrum is indeed more expensive when looking directly at the capital expense. The facility suggested for Kemicentrum requires less treatment steps and the expected annual rainwater usage is larger.

Table 6.6. Comparison of facilities with rainwater collection and consumption.

Data	**Celsiushuset, Uppsala***	**Citypassagen, Örebro***	**Kemicentrum, Lund**
People per day	1,200	460	1,000
Toilets	72	42	173
Rainwater Usage [m^3/year]	1,400	980	2,600
Collection tank [m^3]	180	60	120
Treatment Steps	2 (Sand + UV)	3 (Sand + UV + MF)	1 (MF)
Investment Cost [MSEK]	1.2	0.8**	5.3

*(Holm and Schulte-Herbrüggen, 2021), ** (Jephson and Kristiansson, 2023)

7 Conclusion

A pilot-scale rainwater harvesting system combined with gravity-driven ceramic flat sheet membrane filtration process was successfully applied to rooftop runoff rainwater at Kemicentrum, Lund. The treated rainwater was supplied to two toilets.

The findings indicate that ceramic flat sheet membranes are able to treat rainwater from rooftop runoff. It was showed that pH is neutral after filtration and that the turbidity is reduced. The average rainwater flux and permeability observed were 205 L/m^2/h and 5,000 L/m^2/h/bar respectively. The permeate was clear and odorless and left no residue in the toilets.

Based on the promising pilot-scale results, a full-scale implementation proposal at Kemicentrum, which includes installing a 120 m^3 underground collection tank equipped with a manhole and vortex chamber. Rainwater runoff from 3,700 m^2 roof and 6,300 m^2 parking space would be diverted to this collection tank. Utilizing a ceramic silicon carbide membrane module, the rainwater can be filtered at a constant flux of 20 L/m^2/h to supply all the toilets and washing machines at Kemicentrum.

The economic analysis suggest an investment requirement of about 5.3 MSEK for implementing the rainwater harvesting system. By supplying all toilets and washing machines with rainwater, the facility could reduce its drinking water demand by 2,600 m^3 per year. This would result in a cost of 90 SEK/m^3 for used water, with a technical depreciation time of 20 years.

Overall, the study demonstrates that gravity driven ceramic membrane process for rainwater filtration can offer an uncomplicated and cheap filtration and a sustainable and environmentally friendly solution to reduce potable water consumption. Embracing this technology can help handle the challenges given by climate changes and contribute to water conservation efforts.

The study’s findings provide valuable insights into the feasibility and benefits of implementing rainwater harvesting systems with membrane filtration in urban settings. Further research are recommended to optimize the system, increase efficiency, and promote wider adoption.

8 Future Work

The pilot facility requires manual adjustment and measurements. To begin with would it be of interest to automize the facility and add flow indicators, magnetic valves, pressure indicator, thermometer and level indicators connected to a computer in order to further investigate the performance of the system especially over time and establish a steady operation. Following this, a study on how the ceramic silicon carbide membrane behaves dependent on ion concentration, hardness, pH, temperature, and seasonal differences could be researched.

Furthermore, by installing automatic measuring equipment a cleaning scheme would be easier to establish as one can see patterns of the flux and permeate. The permeability is rapidly decreasing when fouling occurs on the membrane surface as the pores get clogged which would be visible on a continuous data collection and could be predicted rather than manual experiments and inspections. Also, it would be possible for the current system to supply a larger set of toilets.

Another interesting part to look into is the area of use of the rainwater, foremost to wash clothes with it. According to Haq (2017), washing clothes with rainwater requires less detergents, as it is naturally having less hardness than potable water. Validating the theory could be of interest. Also, what other applications at Kemicentrum could use rainwater? Wiping floors and blackboards? Sprinkler system? Replace potable water elsewhere? For instance, for irrigation.

As the total suspended solids analysis was not able to determine the suspended solids in the rainwater it would be of large interest to perform another analysis to determine how well the membrane separate particles from the water. Monitoring the microbial content in the membrane tank to observe how it influences the filtration performance would be of interest. To define the microbial in the water before and after the membrane would be of interest to determine the membrane’s bacteria rejection ability.

References

AHMED, W., VIERITZ, A., GOONETILLEKE, A. & GARDNER, T. 2010. Health Risk from the Use of Roof-Harvested Rainwater in Southeast Queensland, Australia, as Potable or Nonpotable Water, Determined Using Quantitative Microbial Risk Assessment. *Applied and Environmental Microbiology,* 76**,** 7382-7391.

AKPINAR FERRAND, E. & CECUNJANIN, F. 2014. Potential of Rainwater Harvesting in a Thirsty World: A Survey of Ancient and Traditional Rainwater Harvesting Applications. *Geography Compass,* 8**,** 395-413.

AL-RUDAINY, B. 2020. *Galactoglucomannan recovery from softwood spent sulfite liquor: Challenges, process design and techno-economic evaluations.* Doctoral Thesis, Chemical Engineering, Lund University.

ALFVEGREN, J., Electrolux W3130H product details (2024).

AMERICAN PUBLIC HEALTH ASSOCIATION. 1992. *APHA Method 2130: Standard Methods for the Examination of Water and Wastewater* [Online]. Available: https://law.resource.org/pub/us/cfr/ibr/002/apha.method.2130.1992.pdf [Accessed 21 Feb 2024].

ASIF, M. B. & ZHANG, Z. 2021. Ceramic membrane technology for water and wastewater treatment: A critical review of performance, full-scale applications, membrane fouling and prospects. *Chemical Engineering Journal,* 418**,** 129481.

BILTEMA. n.d. *Pumpautomat PA 1301* [Online]. Available: https://www.biltema.se/fritid/tradgard/tradgardspumpar/pumpautomat-pa-1301-2000038619 [Accessed 2 April 2024].

BILTEMA NORDIC SERVICES AB. 2016. *Pumpautomat PA 1301* [Online]. Available: https://docs.biltema.com/v2/documents/file/sv/38e40f16-2afd-45b7-a89b-b05ae26543df [Accessed April 22 2024].

BULLITT CENTER. 2013. *RAINWATER HARVESTING* [Online]. Available: https://bullittcenter.org/building/building-features/waterworks/ [Accessed 5 Feb 2024].

CAMPISANO, A., BUTLER, D., WARD, S., BURNS, M. J., FRIEDLER, E., DEBUSK, K., FISHER-JEFFES, L. N., GHISI, E., RAHMAN, A., FURUMAI, H. & HAN, M. 2017. Urban rainwater harvesting systems: Research, implementation and future perspectives. *Water Research,* 115**,** 195-209.

CEMBRANE A/S. n.d-a. *Drinking Water* [Online]. Available: https://www.cembrane.com/drinking-water [Accessed].

CEMBRANE A/S n.d-b. Technical Brochure for Cembrane SiCBloxTM FX series.

CEMBRANE A/S n.d. Operation & Maintenance Manual for Cembrane SiCBlox FX series Modules.

CHANG, M., MCBROOM, M. W. & SCOTT BEASLEY, R. 2004. Roofing as a source of nonpoint water pollution. *Journal of Environmental Management,* 73**,** 307-315.

CHERYRAN, M. 1998. *Ultrafiltration and Microfiltration Handbook,* CRC Press.

CHRISTENSEN, A.-S. M., Cost of Upscale System, Kemicentrum (2024). E-mail 28 Feb

COWI. n.d. *En innovativ regnvattenslösning sparar på dricksvattnet och skapar en spännande stad* [Online]. Available: https://www.cowi.se/loesningar/vatten/staden-nye-%C3%A5rhus,-danmark [Accessed 1 Feb 2024].

DE BUYCK, P.-J., VAN HULLE, S. W. H., DUMOULIN, A. & ROUSSEAU, D. P. L. 2021. Roof runoff contamination: a review on pollutant nature, material leaching and deposition. *Reviews in Environmental Science and Bio/Technology,* 20**,** 549-606.
FARAGÒ, M., BRUDLER, S., GODSKESEN, B. & RYGAARD, M. 2019. An eco-efficiency evaluation of community-scale rainwater and stormwater harvesting in Aarhus, Denmark. *Journal of Cleaner Production,* 219**,** 601-612.
FOLEY, G. 2013. *Membrane Filtration: A Problem Solving Approach with MATLAB,* Cambridge, Cambridge University Press.
GUILLEN-BURRIEZA, E., THOMAS, R., MANSOOR, B., JOHNSON, D., HILAL, N. & ARAFAT, H. 2013. Effect of dry-out on the fouling of PVDF and PTFE membranes under conditions simulating intermittent seawater membrane distillation (SWMD). *Journal of Membrane Science,* 438**,** 126-139.
HAQ, S. A. 2017. *Harvesting Rainwater from Buildings*, Springer Cham.
HOFS, B., OGIER, J., VRIES, D., BEERENDONK, E. F. & CORNELISSEN, E. R. 2011. Comparison of ceramic and polymeric membrane permeability and fouling using surface water. *Separation and Purification Technology,* 79**,** 365-374.
HOLM, C. & SCHULTE-HERBRÜGGEN, H. 2021. Vattenbesparande åtgärder: Exempelsamling för kommuner och hushåll.
JEPHSON, T. 2023. Att återanvända dag- och regnvatten i fastigheter. *Återvunnet vatten* [Webinar held by Sweden Water Research, VA Syd & Region Skåne].
JEPHSON, T. & KRISTIANSSON, A. 2023. *Inspirationsguide för användning av regn- och dagvatten i fastigheter* [Online]. VA Syd. Available: https://www.vasyd.se/Artiklar/Dagvatten/Inspirationsguide-regnvatten [Accessed 7 Feb 2024].
KOROS, W. J., MA, Y. H. & SHIMIDZU, T. 1996. Terminology for membranes and membrane processes (IUPAC Recommendation 1996). *Journal of Membrane Science,* 120**,** 149-159.
KRETZ, M. 2024. Regnvatten gör rent i wc-stolarna. *Energi&miljö.*
KRÄMER, W., Senior Project Manager at Cembrane A/S (2024). E-mail 2024 April 18
KUS, B., KANDASAMY, J., VIGNESWARAN, S., SHON, H. K. & MOODY, G. 2013. Household rainwater harvesting system – pilot scale gravity driven membrane-based filtration system. *Water Supply,* 13**,** 790-797.
KUSUMAWARDHANA, A., ZLATANOVIC, L., BOSCH, A. & VAN DER HOEK, J. P. 2021. Microbiological Health Risk Assessment of Water Conservation Strategies: A Case Study in Amsterdam. *Int J Environ Res Public Health,* 18.
LARSSON, C., Sales Representative at Uponor Infra AB (2024). E-mail 13 Feb
LILJENSKOG, P., Technical Manager at Castellum (2024). E-mail 15 Feb
LINDBLOM, C., Administrator at Kemicentrum (2024). Email. 5 Feb
LIU, X., REN, Z., NGO, H. H., HE, X., DESMOND, P. & DING, A. 2021. Membrane technology for rainwater treatment and reuse: A mini review. *Water Cycle,* 2**,** 51-63.
LIVSMEDELSVERKET 2022. Livsmedelsverkets föreskrifter (LIVSFS 2022:12). *In:* LIVSMEDELSVERKET (ed.) *2022:12.*
LIVSMEDELSVERKET. 2024a. *Bly* [Online]. Available: https://www.livsmedelsverket.se/livsmedel-och-innehall/oonskade-amnen/metaller1/bly [Accessed April 23 2024].
LIVSMEDELSVERKET. 2024b. *Koppar* [Online]. Available: https://www.livsmedelsverket.se/livsmedel-och-innehall/oonskade-amnen/metaller1/koppar [Accessed April 23 2024].

LUNDS TEKNISKA HÖGSKOLA. 2024. *Schema och läsårsindelning* [Online]. Available: https://www.student.lth.se/mina-studier/schema-och-laesaarsindelning/#c836140 [Accessed 27 March 2024].

LYE, D. J. 2009. Rooftop runoff as a source of contamination: A review. *Science of The Total Environment,* 407**,** 5429-5434.

MAROUFI, N. & HAJILARY, N. 2023. Nanofiltration membranes types and application in water treatment: a review. *Sustainable Water Resources Management,* 9**,** 142.

MELIN, J. 2015. *Här är världens grönaste kontorshus* [Online]. Ny Teknik. Available: https://www.nyteknik.se/energi/har-ar-varldens-gronaste-kontorshus/787505 [Accessed 5 Feb 2024].

NATURVÅRDSVERKET. 2023. *Konsekvenser för teknisk infrastruktur* [Online]. Available: https://www.naturvardsverket.se/amnesomraden/klimatforandringar/klimatet-i-framtiden/effekter-i-sverige/konsekvenser-for-teknisk-infrastruktur/ [Accessed 1 Feb 2024].

NATURVÅRDSVERKET. 2024. *Klimatförändringarnas effekter i Sverige* [Online]. Available: https://www.naturvardsverket.se/amnesomraden/klimatforandringar/klimatet-i-framtiden/effekter-i-sverige/ [Accessed 1 Feb 2024].

NSVA. n.d. *Hur mycket vatten behöver du?* [Online]. Available: https://www.nsva.se/rad-och-tips/skola/vattenexperiment/hur-mycket-vatten-behover-du/#:~:text=R%C3%A4kna%20ihop%20hur%20mycket%20vatten,och%20sedan%20m%C3%A4ta%20upp%20det. [Accessed Feb 12 2024].

ORTEGA SANDOVAL, A. D., BARBOSA BRIÃO, V., CARTANA FERNANDES, V. M., HEMKEMEIER, A. & FRIEDRICH, M. T. 2019. Stormwater management by microfiltration and ultrafiltration treatment. *Journal of Water Process Engineering,* 30**,** 100453.

PARK, W.-I., JEONG, S., IM, S.-J. & JANG, A. 2020. High turbidity water treatment by ceramic microfiltration membrane: Fouling identification and process optimization. *Environmental Technology & Innovation,* 17**,** 100578.

PETER-VARBANETS, M., HAMMES, F., VITAL, M. & PRONK, W. 2010. Stabilization of flux during dead-end ultra-low pressure ultrafiltration. *Water Research,* 44**,** 3607-3616.

PRONK, W., DING, A., MORGENROTH, E., DERLON, N., DESMOND, P., BURKHARDT, M., WU, B. & FANE, A. G. 2019. Gravity-driven membrane filtration for water and wastewater treatment: A review. *Water Research,* 149**,** 553-565.

RATTENBURY, J. M. 2020. *Rainwater Harvesting Fundamentals: Translation of DIN 1989-1:2001-10* [Online]. PDH Center. Available: https://pdhonline.com/courses/c611/Rainwater%20Harvesting%20EN_1989-1_(en).pdf [Accessed 12 Feb 2024].

REWAISE & VA SYD. n.d. *Här finns vi* [Online]. Available: https://rewaise.vasyd.se/Artiklar/Har-finns-vi [Accessed January 24 2024].

SHIGUANG, C., HONGWEI, S. & QUILI, C. 2021. Performance of an innovative gravity-driven micro-filtration technology for roof rainwater treatment *Environmental Engineering Research,* 26.

SIMMONS, G., HOPE, V., LEWIS, G., WHITMORE, J. & GAO, W. 2001. Contamination of potable roof-collected rainwater in Auckland, New Zealand. *Water Research,* 35**,** 1518-1524.

SINGH, R. & HANKINS, N. P. 2016. Chapter 2 - Introduction to Membrane Processes for Water Treatment. *In:* HANKINS, N. P. & SINGH, R. (eds.) *Emerging Membrane Technology for Sustainable Water Treatment.* Boston: Elsevier.
SMHI. 2022. *PTHBV - en areellt högupplöst klimatdatabas för hydrologiska modellberäkningar* [Online]. Available: https://www.smhi.se/kunskapsbanken/hydrologi/pthbv-en-areellt-hogupplost-klimatdatabas-for-hydrologiska-modellberakningar-1.190268 [Accessed 12 Feb 2024].
SMHI. 2024a. *Griddade nederbörd- och temperaturdata - PTHBV* [Online]. Available: https://www.smhi.se/data/ladda-ner-data/griddade-nederbord-och-temperaturdata-pthbv [Accessed 12 Feb 2024].
SMHI. 2024b. *Nederbörd, dygnsvärde* [Online]. Available: https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer/#param=precipitation24HourSum,stations=core,stationid=53430 [Accessed 18 April 2024].
SMHI. 2024c. *Nederbördsavvikelse föregående år* [Online]. Available: https://www.smhi.se/data/meteorologi/ackumulerade-avvikelsekartor/foregaende-ar/nederbord/ [Accessed 31 Jan 2024].
SONAWANE, S., THAKUR, P., SONAWANE, S. H. & BHANVASE, B. A. 2021. Chapter 17 - Nanomaterials for membrane synthesis: Introduction, mechanism, and challenges for wastewater treatment. *In:* BHANVASE, B., SONAWANE, S., PAWADE, V. & PANDIT, A. (eds.) *Handbook of Nanomaterials for Wastewater Treatment.* Elsevier.
SVENSKT VATTEN 2016. *Avledning av dag-, drän- och spillvatten,* Stockholm: Svenskt Vatten.
SVENSKT VATTEN. 2017. *Värt att veta om vatten* [Online]. Svenskt Vatten. Available: https://www.svensktvatten.se/globalassets/fakta-om-vatten/dricksvattenfakta/vart-att-veta-om-vatten_2017.pdf [Accessed 7 Feb 2024].
SWEDEN GREEN BUILDING COUNCIL. n.d. *Innovation inom dagvattenåtervinning: I Celsiushuset spolas det med regnvatten* [Online]. Available: https://www.sgbc.se/nyheter/innovation-inom-dagvattenatervinning-i-celsiushuset-spolas-det-med-regnvatten/ [Accessed January 24 2024].
SWEDISH INSTITUTE FOR STANDARDS 2011. SS-EN 872:2005 Water quality – Determination of suspended solids –

Method by filtration through glass fibre filters.
SZABÓ, R. & ANDA, A. 2018. Drying of water treatment membranes. *Filtration + Separation,* 55**,** 22-27.
SÖRNGÅRD, P., Environmental Expert at Svenskt Vatten (2024). E-mail 19 Feb
THOMAS, T. H. & MARTINSON, D. B. 2007. Roofwater Harvesting: *A Handbook for Practioners*. *Technical Paper Series.* IRC International Water and Sanitation Centre.
UN WATER. n.d. *Water and Climate Change* [Online]. Available: https://www.unwater.org/water-facts/water-and-climate-change [Accessed Jan 18 2024].
UNITED NATIONS. 2016. *Water Action Decade* [Online]. Available: https://www.un.org/sustainabledevelopment/water-action-decade/ [Accessed January 17 2024].
UNITED NATIONS. n.d. *Water Scarcity* [Online]. UN Water. Available: https://www.unwater.org/water-facts/water-scarcity [Accessed January 17 2024].

UPONOR INFRA AB. n.d. *Frågor och svar: Hur lång är livslängden på en anläggning?* [Online]. Available: https://www.uponor.com/sv-se/infra/service/faq [Accessed April 12 2024].
VA SYD. 2023a. *Hållbar vattenanvändning* [Online]. Available: https://www.vasyd.se/Artiklar/Hallbar-vattenanv%C3%A4ndning [Accessed 17 Jan 2024].
VA SYD. 2023b. *Rätt vatten till rätt sak* [Online]. Available: https://www.vasyd.se/Artiklar/Forskning-utveckling-och-innovation/ratt-vatten-till-ratt-sak [Accessed Jan 17 2024].
VA SYD. 2024. *Taxebilaga 2 - Brukningsavgifter Lunds kommun (inkl. moms)* [Online]. Available: https://www.vasyd.se/-/media/Dokument_ny_webb/Taxor/Avgifter-for-vatten-och-avlopp/2024/Taxebilaga-2-Lund-2024.pdf [Accessed March 6 2024].
VIALLE, C., SABLAYROLLES, C., LOVERA, M., HUAU, M. C., JACOB, S. & MONTREJAUD-VIGNOLES, M. 2012. Water Quality Monitoring and Hydraulic Evaluation of a Household Roof Runoff Harvesting System in France. *Water Resources Management,* 26**,** 2233-2241.
VILLARREAL, E. L. & DIXON, A. 2005. Analysis of a rainwater collection system for domestic water supply in Ringdansen, Norrköping, Sweden. *Building and Environment,* 40**,** 1174-1184.
WANG, Y.-N. & WANG, R. 2019. Chapter 1 - Reverse Osmosis Membrane Separation Technology. *In:* ISMAIL, A. F., RAHMAN, M. A., OTHMAN, M. H. D. & MATSUURA, T. (eds.) *Membrane Separation Principles and Applications.* Elsevier.
WARSINGER, D. M., CHAKRABORTY, S., TOW, E. W., PLUMLEE, M. H., BELLONA, C., LOUTATIDOU, S., KARIMI, L., MIKELONIS, A. M., ACHILLI, A., GHASSEMI, A., PADHYE, L. P., SNYDER, S. A., CURCIO, S., VECITIS, C. D., ARAFAT, H. A. & LIENHARD, J. H. 2018. A review of polymeric membranes and processes for potable water reuse. *Progress in Polymer Science,* 81**,** 209-237.
WHO. 2017. *Water Quality and Health - Review of Turbidity: Information for regulators and water suppliers* [Online]. Available: https://iris.who.int/bitstream/handle/10665/254631/WHO-FWC-WSH-17.01-eng.pdf?sequence=1 [Accessed 26 March 2024].
YANG, Z., ZHOU, Y., FENG, Z., RUI, X., ZHANG, T. & ZHANG, Z. 2019. A Review on Reverse Osmosis and Nanofiltration Membranes for Water Purification. *Polymers,* 11.

Appendix A: Historical precipitation in Lund 2002-2023

Table A1. Historical precipitation monthly each year in Lund from 2002 to 2023. The precipitation is measured in millimeter and collected from SMHI (2024c).

Month / Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-02	109.8	108.5	38.5	35.6	62.8	107.1	77.8	33.8	22.2	129.4	64.2	35.8
-03	53.2	10.4	11.6	53.3	65.8	63.2	79.3	52.5	37.6	59.7	72.1	74.3
-04	79.4	39.3	55.3	29.3	24	95.1	131.2	78	49.9	81	66.5	73.5
-05	64.1	54.7	46.4	9.5	48.5	59.5	87.7	59.6	20.6	60.3	52.7	71.9
-06	24.8	51.5	38.6	58.8	75	31.5	15	242.3	34.1	100.2	91.8	96.8
-07	124	59	41.5	21.1	59.1	138.3	227.6	57.1	85.3	38.4	44.9	60.8
-08	74.1	29	84.3	44.5	34.6	31.3	51.4	155.4	30.1	95.8	65.8	72.1
-09	30.9	48	41.8	13.1	60	74.3	72.1	59.4	39.2	68.1	104.1	63.3
-10	33.4	53.3	36	22.4	57	56.4	25.3	190.3	62.6	68.2	120.8	73.2
-11	60.9	38.2	44.9	18.4	68.5	85.4	173.2	141.5	62.3	53.5	12.2	81.5
-12	107.5	46.3	13.9	41.9	25.4	76	65	47.6	61.5	76.4	66	82.3
-13	65.8	33.6	11.3	19.3	44.6	89.1	26.1	68.6	63	93.9	76	78.8
-14	70.9	60.1	34	36.1	67.9	54.2	61.1	165.7	43	140.2	34.1	128.9
-15	101.2	25.1	70.3	32.2	63	52.2	65.1	57.5	81.2	19.4	163.1	99.3
-16	45.5	53.5	36.4	59.8	18.5	89.2	91.9	62.9	21	82.9	71.3	45.1
-17	27.6	69.4	53	52.7	30.9	120	77.6	72.3	112	104.8	83.8	86.6
-18	75.2	30.6	62	39.7	4.8	26.7	8.8	94.5	32.7	66.4	29	79.4
-19	60.2	62.8	110.4	14.6	39.2	63.6	56.6	64	96.4	88.6	55.4	63.9
-20	92.5	85.1	25.7	18.3	32.2	54.6	65.6	56.8	61.9	96.5	37	63.8
-21	80.1	31.2	50.2	29.9	68.8	13.3	94.6	121.6	80.1	97.3	58	88.2
-22	64.3	114.6	0.8	49.3	72.3	54.3	55.4	37.6	77.7	46.9	27.3	85.5
-23	118.2	58.9	91.8	23.5	13.2	23.9	128.4	184.7	26.8	125.5	110.6	99.2

Appendix B: Economic Calculations

Technoeconomic analysis

	Metrics	Data	Unit	Function	Source
5	Annual fee for stormwater	1.39	SEK/m^2 lot	=0.695+0.695	https://www.vasyd.se/-/media/Dokument_ny_webb/Taxor/Avgifter-for-vatten-och-avlopp/2024/Taxebilaga-2-Lund-2024.pdf
6	Fee drinking water	11.94	SEK/m^3		https://www.vasyd.se/-/media/Dokument_ny_webb/Taxor/Avgifter-for-vatten-och-avlopp/2024/Taxebilaga-2-Lund-2024.pdf
8	Nr. toilets in Kemicentrum	173	-		Caroline Lindblom
9	Nr. people in Kemicentrum	1000	daily		Caroline Lindblom
10	Available roof area	20000	m^2		
11	Available parking surface	9000	m^2		
12	Daily toilet usage	6	L/person/flush		https://vard.skane.se/skanes-universitetssjukhus-sus/undersokningar-och-behandlingar/trana-urinblasan/
13	Collection factor roof	0.9	-		P110 Svenskt Vatten
14	Collection factor asphalt	0.8	-		P110 Svenskt Vatten
15	Volume water per flush	6	L		Svenskt Vatten
16	Avg. rainwater per month	64	L	=ROUND(SUM(M6#/12);0)	
18	**Toilet**				
19	Toilet visit per work day per person (office)	2	-		https://pdhonline.com/courses/c611/Rainwater Harvesting EN_1989-1_(en).pdf
20	Tot nr. flushes per day	2000	-	=B19*D9	
21	Volume flush water per day	12	m^3/day	=B20*B15/1000	https://pdhonline.com/courses/c611/Rainwater Harvesting EN_1989-1_(en).pdf
22	Volume flush water per month	240	m^3/month	=B21*20	
23	Volume flush water per school year	2400	m^3/year	=B21*200	
26	**Laundering**				
27	Water consumption: Electrolux W555H	53	L/wash		Electrolux
28	Water consumption: Electrolux W575H	62	L/wash		Electrolux
29	Water consumption: Electrolux W3130H	132	L/wash		Jonas Alfvegren Electrolux
30	Washes per day	1	Per machine		
31	Daily water requirement	0.25	m^3	=ROUND(SUM(B27:C29)*B30/1000;2)	
32	Monthly water requirement	5	m^3	=B31*20	
33	Annual water requirement	50	m^3	=B31*200	
35	**Water demand Kemicentrum**				
36	Daily	13	m^3	=ROUNDUP(B31+D21;0)	
37	Monthly	260	m^3	=ROUND(B36*20;0)	
38	Annually	2600	m^3	=ROUND(B37*10;-2)	

Figure B1. Data of cost for drinking water, number of toilets and personnel, and water consumption at Kemicentrum.

	A	B	D	F	G
40	**Required surface area**				
41	From roof to meet monthly demand	4500	m^2	=ROUND(B37/(AVERAGE(M6#)*10^-3*B13);-2)	
42	From parking lot to meet monthly demand	5100	m^2	=ROUND(B37/(AVERAGE(M6#)*10^-3*B14);-2)	
44	**Roof runoff**				
45	Avg. runoff per month to meet demand	300	m^3	=ROUNDUP(AVERAGE(M7:X7);-2)	
46	Avg. collectable runoff/month to meet demand	270	m^3	=ROUND(B45*B13;-1)	
47	Avg. whole roof runoff	1300	m^3	=ROUND(B10*AVERAGE(M6:X6)/1000;-2)	
48	Avg. collectable runoff whole roof	1200	m^3	=ROUND(B47*B13;-2)	
50	**Parking lot**				
51	Avg. runoff per month to meet demand	375	m^3	=ROUND(B52/B14;0)	
52	Avg. collectable runoff per month to meet demand	300	m^3	=ROUND(SUM(M8:X8)/12;-2)	
53	Avg. runoff whole parking surface	600	m^3	=ROUND(B11*AVERAGE(M6:X6)/1000;-2)	
54	Avg. collectable runoff whole parking surface	500	m^3	=ROUND(B53*B14;-2)	
57	**Savings**				
58	Roof: Saved on rainwater/month	3200	SEK/month	=ROUND(B6*B46;-2)	
59	Parking: Saved on rainwater/month	4500	SEK/month	=ROUND(B6*B51;-2)	
62	**Costs**				
63	Collection tank Parking Lot	558000	SEK		Uponor
64	Collection tank Green Surface	396000	SEK		Uponor
65	Vortex Chamber	154000	SEK		Uponor
66	Membrane modules	1530000	SEK		Split Water Nordics
67	Pump	18000	SEK		Split Water Nordics
68	Insulated Container	37500	SEK		Split Water Nordics
69	Automatic CIP system	108000	SEK		Split Water Nordics
71	Scenario Parking Lot	2405500	SEK		
72	Scenario Green Surface	2243500	SEK		

Figure B2. Required catchment area, rain runoff, savings of using rainwater instead of drinking water and the CAPEX for the facility.

	A	B	C	D	E	F
62	**Costs**					
63	***Machine Parts***					
64	Collection tank Parking Lot	558000		SEK		Uponor
65	Collection tank Green Surface	396000		SEK		Uponor
66	Vortex Chamber	154000		SEK		Uponor
67	Membrane modules	1530000		SEK		Split Water Nordics
68	Pump	18000		SEK		Split Water Nordics
69	Automatic CIP system	108000		SEK		Split Water Nordics
70						
71	**SUM: Parking Lot**	2368000		SEK		
72	**SUM: Green surface**	2206000		SEK		
73						
74						
75	***Ground and Concrete Work***					
76	Earth shafting	72000		SEK		240 m^3
77	Filling	60000		SEK		120 m^3
78	Water pipe from collection to membrane	375000		SEK		250 m
79	Hard surfaces	96000		SEK		240 m^2
80	**SUM**	603000				
81						
82	***Construction***					
83	Reconstruction of room	500000		SEK		250 m^2
84	**SUM**	500000				
85						
86	***Plumbing, Heating, Ventilation***					
87	Ventilation	100000		SEK		
88	Plumbing & Heating	100000		SEK		Installation
89	Reconnection to existing toilets	250000		SEK		
90	**SUM**	450000				
91						
92	***Electricity & Automation***	700000		SEK		
93	**SUM**	700000		SEK		

Figure B3. Entrepreneur cost of the facility.

	A	B	C	D	E	F
93	**SUM**	700000		SEK		
94						
95	***Unpredictable***	693150		SEK		
96						4621000
97	***Total entrepreneur costs***					
98	Parking lot	5314150		SEK		
99	Green surface	4459000		SEK		
100						
101	Depreciation Time	20		Years		Cembrane lifespan
102						
103	**Parking Lot**					
104	Depreciation Parking lot	265707.5		SEK/year	=B98/B101	
105	Savings	31000		SEK/year	=ROUND(B38*B6;-3)	
106	Cost per m^3	90		SEK/m^3	=(B104-B105)/B38	
107	Payoff time	171		years	=ROUND(B98/B111;0)	
108						
109	**Green Surface**					
110	Depreciation Green surface	222950		SEK/year	=B99/B101	
111	Savings	31000		SEK/year	=ROUND(B38*B6;-3)	
112	Cost per m^3	70		SEK/m^3	=ROUND((B110-B111)/B38;-1)	
113	Payoff Time	144		years	=ROUND(B99/B111;0)	
114						

Figure B4. Depreciation per year, corresponding cost per cubic meter and payoff time of the parking lot case and green surface case.

	K	L	M	N	O	P	Q	R	S	T	U	V	W
5	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6	mm	71	53	45	33	47	66	79	96	55	82	68	77
7	Roof: m^3/month (demand)	290	210	180	130	190	270	320	390	220	330	280	310
8	Parking: m^3/month (demand)	290	220	180	130	190	270	320	390	220	330	280	310
11	Monthly demand	260 m^3											
12	Average monthly rain	0.064333 m^3/m^2		-->	collectable	0.054683 m^3/m^2		-->		550 m^3		average collectable	
15	How large surface?	10000 m^2		-->	Roof	3700 m^2		+	Parking lot	6300 m^2			
17	Collectable rain	640	480	410	300	420	590	710	860	500	740	610	690
18	Demand	260	260	260	260	260	260	260	260	260	260	260	260
19	Excess water after use	380	220	150	40	160	330	450	600	240	480	350	430
25	**Membrane**												
26	Active area per module	6.9 m^2											
27	Operation	12 h/day											
28	Rate	1.1 m^3/h		-->		1100 L/h							
29	Theoretical flux	159 L/m^2/h											
31	Obtained flux, J	20 L/m^2/h											
32	Required area dep flux	55 m^2											
33	Required modules	8											

Figure B5. Monthly precipitation, runoff from the catchment surfaces, monthly demand, collectable runoff, and how much excess water will be collectable after use. Calculation of required size of membrane facility in the box down to the left.

Appendix C: Measurements

Test	Time [min]	Volume [m³]	Flux [L/m²/h]	Pressure [bar]	Permeability [L/m²/h/bar]	Comment
A.1	23	0.392	148	0.074	2000	A. From full membrane tank down to the valve
A.2	21	0.392	162	0.074	2189	Clean water
A.3	21.5	0.392	159	0.074	2149	

Test	Time [min]	Volume [m³]	Flux [L/m²/h]	Pressure [bar]	Permeability [L/m²/h/bar]	Comment
B.1.1	1.1	0.056	443	0.064	6922	B. 5 cm below overflow pipe. 10 cm emptied from membrane tank to permeate tank at a time
B.1.2	1.43	0.056	341	0.054	6315	Clean water
B.1.3	1.67	0.056	292	0.044	6636	
B.1.4	1.9	0.056	256	0.034	7529	
B.1.5	2.87	0.056	170	0.025	6800	
B.1.6	4.73	0.056	103	0.015	6867	
B.1.7	25	0.056	19	0.005	3800	
B.2.1	1.12	0.056	435	0.064	6797	
B.2.2	1.42	0.056	343	0.054	6352	
B.2.3	1.68	0.056	290	0.044	6591	
B.2.4	1.87	0.056	260	0.034	7647	
B.2.5	2.97	0.056	164	0.025	6560	
B.2.6	4.78	0.056	102	0.015	6800	
B.2.7	23.9	0.056	20	0.005	4000	
B.3.1	1.1	0.056	443	0.064	6922	
B.3.2	1.32	0.056	369	0.054	6833	
B.3.3	1.58	0.056	308	0.044	7000	
B.3.4	1.98	0.056	246	0.034	7235	
B.3.5	2.8	0.056	174	0.025	6960	
B.3.6	4.93	0.056	99	0.015	6600	
B.3.7	24.1	0.056	20	0.005	4000	

Test	Time [min]	Volume [m³]	Flux [L/m²/h]	Pressure [bar]	Permeability [L/m²/h/bar]	Comment
C.1	34	1.114	285	0.034	8382	C. Full storage tank before membrane tank. Full membrane tank. Empty permeate. Open valves until no flow
C.2	33	1.114	294	0.034	8647	Clean water and average pressure
C.3	34	1.114	285	0.034	8382	

Test	Time [min]	Volume [m³]	Flux [L/m²/h]	Pressure [bar]	Permeability [L/m²/h/bar]	Comment
D.1	29	1.052	315	0.034	9265	D. Both storage tank full. Membrane tank full. Empty permeate. All communicating valves open
D.2	32	1.052	286	0.034	8412	Clean water and average pressure
D.3	30	1.052	305	0.034	8971	

Test	pH	Column2	Avg.	St.dev	Column3	Comment
E.1	6.57		6.63	0.012		E. pH rainwater
E.2	6.58					22-mar
E.3	6.6					
E.4	6.66					
E.5	6.7					
E.6	6.69					

Membrane tank	Height [m]	Water pillar [m]	Water pressure ex. height
	1.75	0.65	0.0981

Volumetric Flow	Average	St.dev
1023	1079	41
1120		
1094		

Height	Mean	Pressure	Permeability [L/m²/h/bar]	St.dev Flux	St.dev Perm	Column2
60	440	0.064	6875	4	59	
50	351	0.054	6500	13	236	
40	297	0.044	6750	8	183	
30	254	0.034	7471	6	173	
20	169	0.025	6760	4	164	
10	101	0.015	6733	2	113	
0	20	0.005	4000	0	94	
	Average: 269		Average: 6848	Average: 6	Average: 155	

Figure C1. Tap water flux test and pH.

Test	pH	Column2	Avg.	St.dev	Column3	Comment
F.1	7.7		7.663333333	0.026246693		F. pH tapwater
F.2	7.64					
F.3	7.65					

Test	Filter	Volume	Pan	Final	TSS	Comment
G.1.1	0.1376	980	1.8026	0.1383	0.714285714	G. TSS rainwater
G.1.2	0.1372	980	1.7973	0.1377	0.510204082	Without pre-drying filter
G.1.3	0.1377	980	1.8083	0.1385	0.816326531	
G.2.1	0.1378	940	0	0.1382	0.425531915	With pre-drying
G.2.2	0.137	970	0	0.1376	0.618556701	
G.2.3	0.1374	980	0	0.1377	0.306122449	

Avg.	St.dev
0.6	0.17
0.7	0.13
0.5	0.13

Test	Turbidity	Comment	Date
H.1.1	3	H. Turbidity	26-mar
H.1.2	4	Rainwater	
H.1.3	3	Unfiltered	
H.1.4	4		
H.1.5	3		
H.1.6	3		
H.1.7	4		
H.1.8	3		
H.1.9	3		
H.2.1	0	Tap water	
H.2.2	0		
H.2.3	0		
H.3.1	7	Rainwater	02-apr
H.3.2	6	Unfiltered	
H.3.3	6		
H.4.1	1	Rainwater	05-apr
H.4.2	1	Filtered	
H.4.3	1		
H.5.1	4	Rainwater	
H.5.2	4	Unfiltered	
H.5.3	4		

Avg. U-rain	St.dev U-rain
4	1.2

Avg. F-rain	St.dev F-rain
1	0

Test	pH	Column2	Avg	St.dev	Column3	Comment
I.1	7.24		7.3	0.046		I. pH filtered rainwater
I.2	7.35					
I.3	7.32					

Figure C2. pH tap water, TSS measurement for rainwater and turbidity measurement for tap water, unfiltered rainwater and filtered rainwater.

Test	pH	Column2	Avg	St.dev	Column3	Comment
I.1	7.24		7.3	0.046		I. pH filtered rainwater
I.2	7.35					
I.3	7.32					

Test	Time [min]	Volume [m³]	Flux [L/m²/h]	Pressure	Permeability	Comment
J.1.1	1.15	0.056	423	0.064	6609	B. 5 cm below overflow pipe. 10 cm emptied from membrane tank to permeate tank at a time
J.1.2	1.42	0.056	343	0.054	6352	
J.1.3	1.88	0.056	259	0.044	5886	
J.1.4	2.4	0.056	203	0.034	5971	
J.1.5	3.85	0.056	126	0.025	5040	
J.1.6	6.08	0.056	80	0.015	5333	
J.1.7	28	0.056	17	0.005	3400	
J.2.1	1.3	0.056	375	0.064	5859	
J.2.2	1.68	0.056	290	0.054	5370	
J.2.3	2.03	0.056	240	0.044	5455	
J.2.4	2.92	0.056	167	0.034	4912	
J.2.5	4.17	0.056	117	0.025	4680	
J.2.6	7.2	0.056	68	0.015	4533	
J.2.7	29	0.056	17	0.005	3400	
J.3.1	1.67	0.056	292	0.064	4563	
J.3.2	2.18	0.056	223	0.054	4130	
J.3.3	2.67	0.056	182	0.044	4136	
J.3.4	3.47	0.056	140	0.034	4118	
J.3.5	5.2	0.056	94	0.025	3760	
J.3.6	8.83	0.056	55	0.015	3667	
J.3.7	35	0.056	14	0.005	2800	

Height	Avg	Pressure	Permeability	St.dev Flux	St.dev Perm	Column1
60	363	0.064	5672	54	845	
50	285	0.054	5278	49	909	
40	227	0.044	5159	33	744	
30	170	0.034	5000	26	759	
20	112	0.025	4480	13	539	
10	68	0.015	4533	10	680	
	16	0.005	3200	1	283	
	Average: 204		Average: 5020	Average: 31	Average: 746	

Figure C3. pH for permeate and rainwater flux measurements.

Appendix D: Entrepreneur Costs

Table D.1. Summary of entrepreneur costs for the membrane facility.

Object	Cost [SEK]	Comment
Machine		
Collection tank	558,000	120 m^3
Vortex Chamber	154,000	550 L
Membrane Modules	1,530,000	8 modules
Pump	180,000	
Automatic CIP	108,000	
Total Machine	*2,368,000*	
Ground and Concrete Work		
Shafting	72,000	240 m^3
Filling	60,000	120 m^2
Hard Surfaces	96,000	250 m^2
Water pipes from collection tank to membrane	375,000	250 m
Total Ground and Concrete Work	*603,000*	
Construction		
Reconstruction of a room	500,000	250 m^2
Total Construction	*500,000*	
Heat, Plumbing and Ventilation		
Ventilation System	100,000	
Heat and Plumbing	100,000	
Reconnection to existing toilets	250,000	
Total Heat, Plumbing and Ventilation	*450,000*	
Electricity and Automation		
Electricity and Automation	700,000	
Total Electricity and Automation	*700,000*	
Total Costs	*4,621,000*	
Unpredictable	*693,150*	15% of total costs
Total Investment Cost	5,314,150	

Appendix E: Calculations of Technical Depreciation Time

The corresponding price of water based on the capital expenditure (CAPEX), technical depreciation time, savings from municipal water fees and the water consumption is calculated with Equation E.1.

$$Price\ of\ water\ (SEK/m^3) = \frac{\frac{CAPEX\ (SEK)}{Depreciation\ Time\ (Years)} - Savings\ (SEK/year)}{Annual\ Rainwater\ Consumption\ (m^3/year)} \quad (E.1)$$