Suitable treatment of source separated greywater for discharge into an Urban Environment

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Water and Environmental Engineering
Department of Chemical Engineering
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By

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Picture on front page: Vision of Helsingborg site. Photo by City of Helsingborg.

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Preface

I am extremely grateful for the opportunity to work on this thesis project. It has been both enlightening and challenging. Special gratitude to my external supervisor, Hamse Kjerstadius for according me the opportunity to work on this topic together with NSVA. Thank you for being kind and patient while tirelessly guiding me through the course of this thesis. I would express my sincerely gratitude to my academic supervisor, Åsa Davidsson, for allowing to supervise my work and for the continued support through the course of the thesis.

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To my friends, thank you for constantly checking on me. To teammates at Lunds VK, you made my stay in Lund fun and worthwhile. To the International Fellowship at Pingstkyrkan Lund, thank you for the friendship, the prayers and encouragements.

Last but not least, I am grateful to God for giving me the strength to complete this thesis project.

Summary

It can no longer be refuted that greywater reuse is paramount to curbing the persistent global water crisis. Of the domestic wastewaters, greywater is less polluted than blackwater, but treatment is still necessary to make it safe for reuse. The most common greywater reuse application is toilet flushing. However, the use of vacuum toilets in the Oceanhamnen project, covered in this thesis, means that another greywater reuse application besides toilet flushing is required. One of the proposed greywater reuse applications is recreational purposes i.e. a water park.

NSVA and the city of Helsingborg are in the process of constructing residential houses to accommodate roughly 2000 people in the Oceanhamnen area. The houses are fitted with source separating technology. An interesting opportunity is that the greywater generated from housing units could be discharged into the surrounding urban environment. However, for greywater to be discharged into a water park, water regulations dictate that the greywater is treated to ensure a safe discharge.

This thesis study aims to recommend a suitable treatment method or a combination of treatment methods that would allow for a safe discharge of treated greywater in to the water park in the Oceanhamnen area. Selection criteria are formulated in order to narrow the scope of the literature review and site visits. A number of relevant treatment methods are found using these selection criteria. Evaluation criteria are also formulated and used to further evaluate the selected treatment methods.

Following the *selection criteria*, the following treatment methods are selected; the Rotating Biological contactor (RBC), Moving Bed Biofilm Reactor (MBBR), Membrane Bioreactor (MBR) Constructed wetland and the combined aerobic biofilter & constructed wetland treatment systems. The selected treatment methods are further evaluated using the *evaluation criteria*. Both the MBR and MBBR systems are deemed successful for treating greywater for reuse though there is need to improve P removal abilities of each system. In line with the aim of this thesis study, the MBBR system is the preferred choice (to the MBR system) as suitable greywater treatment for urban discharge (a water park) in Oceanhamnen.

Table of Contents

List of Abbreviations

GW	Greywater
BOD	Biochemical oxygen demand
TOC	Total Organic Carbon
N	Nitrogen
P	Phosphorus
RWF	Roof Water Farm
MBBR	Moving Bed Biofilm Reactor
MBR	Membrane Bioreactor
RBC	Rotating Biological contactor
SBR	Sequence batch reactor
CW	Constructed Wetland
NSVA	Nordvästra Skånes Vatten och Avlopp AB
cfu	colony forming unit
NTU	Nephelometric Turbidity Unit (NTU)
WWTP	Wastewater Treatment Plant

1. Introduction

Greywater (GW) treatment and reuse could be an efficient way to reduce wastage of water (Edwin et al., 2013). This is crucial especially in recent times characterized by increasing water scarcity and stress on water resources. Systems for greywater treatment and reuse are a form of water resource management (Edwin et al., 2013). In recent years, governments and water bodies in water management are promoting greywater treatment systems as a possible solution for reducing water scarcity (Edwin et al., 2013).

Greywater generation is not climate dependent e.g. compared to other sources of better quality water such as rainfall harvesting (Leong et al., 2017). A GW treatment system thus receives consistent GW supply throughout the year. GW treatment systems in urban, highly populated areas result in larger and more consistent volumes of greywater for treatment, hence an undisrupted supply of GW for the desired reuse purpose. This further elucidates why greywater treatment and reuse is fast growing in interest to many water researchers and is of vital importance to the project in Helsingborg. Greywater recycling on a large scale means that even greater reuse purposes can be attained since large volumes of greywater are recovered.

Greywater reuse is generally a novel field. The reuse of greywater has only been possible following the successful operation of source separated systems. Such source separated systems are not common because they require a larger footprint and hence this practice is mainly common as decentralized treatment systems for small households (Günther, 2000). Currently, some of the greywater reuse applications include toilet flushing (Nolde et al., 2016; Friedler et al., 2005), agriculture i.e. irrigation of gardens and support of aquatic and plant life; an example is the Roof Water Farm in Berlin (Nolde et al., 2016). Other possible and generally acceptable greywater reuse applications include: groundwater recharge (Jenssen, 2005), cooling and fire suppression systems (Nnaji et al., 2013). Another greywater reuse application would be utilization of the treated effluent as a drinking water source. However, developed countries such as Sweden have stringent drinking water regulations (Livsmedelsverket, 2001) which restricts its application. Unless effluent quality is good enough to convince legislators and the general public of meeting drinking water, greywater reuse might never be accepted as a drinking water source. The cost of drinking water in some European countries such as Germany is affordable which makes it even harder to convince the populations to opt for treated greywater (Nolde and Arinaitwe, 2018).

1.1 Background to the project

Source separation of wastewater has many potential benefits such as nutrient recovery from blackwater and heat recovery from greywater (Larsen et al., 2013). The Nordvästra Skånes Vatten och Avlopp AB (NSVA) in cooperation with the city of Helsingborg, is in the process of constructing residential homes that will accommodate roughly 2000 people. The residential area of Oceanhamnen will comprise of 450 households and buildings for 1800 office workers, in which, source separation of wastewater is being implemented right from the construction phase.

1.2 Treatment of greywater

Greywater is considered relatively clean when compared with blackwater and therefore many scientists have suggested that if treated sufficiently, greywater could supplement fresh water supply (Günther, 2000; Gross et al., 2015). Large amounts of greywater are expected to be produced from these newly constructed households in Oceanhamnen. Since roughly 62% of the water consumed in households (with water closet toilets) becomes greywater (Edwin et al., 2013); for a water consumption rate of 100 l/p/d (Jönsson et al., 2005), the resulting greywater produced is equal to 124,000 litres/day (62% x 100 x 2 000). In order to elevate people's awareness about the water cycle, NSVA is considering different ways in which the produced greywater may be locally reused in the city and surrounding areas.

Once treated, greywater can be reused in a number of ways such as irrigation, cooling systems, fire suppression systems among others (Gross et al., 2015). One of such ways would be to discharge the resulting treated greywater into Helsingborg city in the form of a water park where people including children could visit, sit and play and relax in the cool environment. The parks could further improve the aesthetics in the city. Another important aspect with developing such water parks is the increase in citizen's awareness about the urban cycles of water and wastewater and as such could help to create a link between the people and the municipal water companies since people are able to benefit directly from them e.g. relaxation areas.

1.3 Problem description

An important focus for projects on greywater treatment and reuse is to ensure that treated and hygienically safe greywater is discharged into an urban area; a park area or a water installation. One big concern arising with discharge of treated greywater into an urban area or any receiving water is the possibility for pathogen pollution. Microbial pollution poses risks such as illness to humans from exposure to contaminated water (Benami et. al, 2016; Etchepare and van der Hoek, 2015). Other concerns include; ensuring that nitrogen (N), phosphorous (P) and organic matter discharge to receiving waters does not lead to eutrophication and anaerobic conditions (results in odor) in the receiving waters (SEPA, 2000). Therefore, GW treatment and reuse in urban environments such as Oceanhamnen raises critical issues with regards to what treatment system must be used in order to achieve a sufficiently safe effluent.

In order to allow safe discharge of treated greywater in an urban environment, the greywater needs to be treated for wastewater pollutants such as organic compounds, nutrients and pathogens. Thus, NSVA would need knowledge about suitable greywater treatment technologies to achieve safe discharge in to an urban environment. This thesis project was therefore, envisaged to come up with a detailed study into the different methods for greywater treatment and better yet, a specific treatment method that could be employed in Helsingborg area to meet NSVA's envisioned greywater treatment and reuse for local discharge in the surrounding areas.

1.4 Aim and goal of the thesis

The aim of the thesis was to evaluate greywater treatment technologies that can be applied in order to achieve a safe surface discharge of treated greywater back into the urban dense environment. The goal of the thesis study is to suggest a suitable greywater treatment method for the Oceanhamnen area in Helsingborg.

1.5 General Methodology

A literature review/study, site visits and consultations with selected experts on greywater and greywater treatment methods were used to obtain extensive information throughout the course of the thesis project.

1.6 Delimitations

Social acceptance of the greywater systems proposed is crucial if the system is to meet the expected design functions, however, for the purposes of this thesis, only the technical aspects of the greywater systems are considered.

2 Greywater

Greywater is generated from showers, baths, hand wash basins, laundry/washing machines and may also include wastewater from kitchen sinks, dishwashers but excludes streams from toilets. Greywater accounts for 50 - 80% of the total household water consumption (Eriksson et al, 2002). Highly polluted greywater refers to greywater generated from showers, kitchen and laundry whereas Low polluted greywater refers to greywater generated from showers / baths only (Boyjoo et al., 2013). Figure 2.1 illustrates how much greywater is produced in relation to the total water consumed in a household for India.

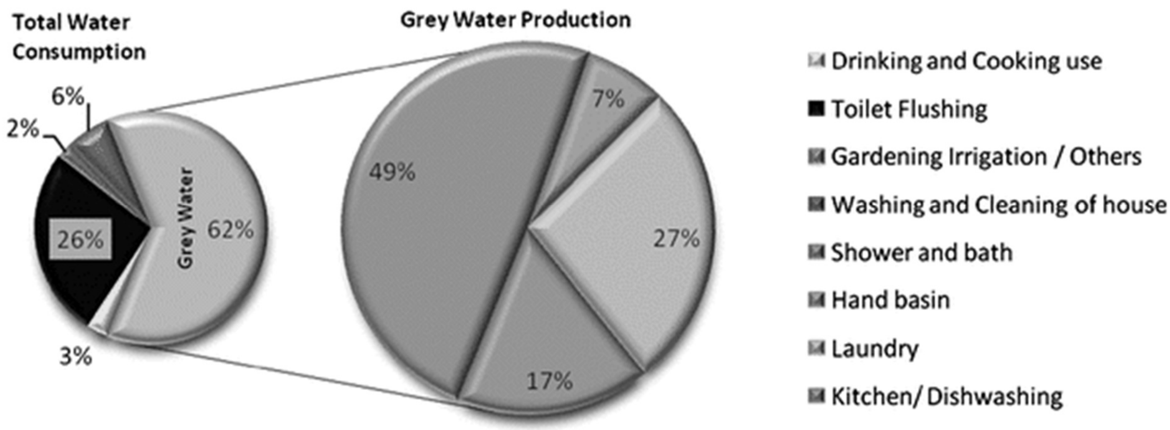

Figure 2.1. The relative distribution of total water consumption and greywater production in India (Edwin et al., 2013). Published with permission from Springer.

According to Figure 2.1, showers and baths form an important part of the greywater systems, accounting for 49% of the total greywater production. Wastewater generated from washing and cleaning houses accounts for 6% of the total water consumption and is treated as blackwater. In developed countries such as Sweden, wastewater generated from washing and cleaning of houses is usually included in the greywater; therefore a considerably higher greywater production may be realized in developed countries compared with developing countries such as India.

Morel and Diener suggests that the volume of greywater generated depends on the lifestyles, population structures (age, gender), living standards, customs and habits, degree of water abundance and water installations (*Morel and Diener*, *2006* cited in Li, Wichmann and Otterpohl, 2009; Gross et al., 2015). Typical greywater volumes range from 90 - 120 l/p/day to as low as 20 to 30 l/p/day in low income countries that are characterised by water scarcity (*Morel and Diener*, 2006 cited in Li, Wichmann and Otterpohl, 2009). In Sweden, the typical greywater volume generated is 100 l/p/day (*Vinnerås et al., 2005* cited in Jönsson et al., 2005).

2.1 Greywater composition

Greywater composition is highly variable due to its dependency on a number of factors such as the size of population, population structures (age and gender), lifestyles and consumption habits among others. Donner et al. (2010) also argues that the variations in greywater composition is attributed to the dynamics and behaviour of the households' occupants, and thus reflecting the inhabitants' age distribution, lifestyles, water use tendencies, and consumer choices (e.g. choice of cleaning and personal care products, choice of shower head etc.).

From Table 2.1, it is evident that kitchen wastewater has the highest organic matter and nitrogen load. It can contain highly polluting and putres-cible compounds that are not desired in a greywater treatment system (Christova-Boal et al., 1996). This could further elucidate why kitchen wastewater is often excluded from greywater stream in some countries. However, for the purposes of this thesis study, the greywater in consideration contains kitchen wastewater. Mixed greywater (i.e. greywater containing bathroom, laundry and kitchen greywater) has a low nitrogen and phosphorus loading than bathroom, laundry and Kitchen respectively.

Table 2.1. General characteristics of greywater for the different household sources i.e. bathrooms, laundry, mixed one with a combination of kitchen, laundry and bathroom greywater and kitchen (Donner et. al, 2010). Donner et al., 2010 generated the values presented in the table below from a combination of various information from different scientific papers. The last column in the table presents the composition of household raw greywater in Sweden (Jönsson et al., 2005).

Parameter	**Bathroom**	**Laundry**	**Kitchen**	**Mixed**	**Swedish household GW** (Jönsson et al., 2005)
BOD (mg/l)	26-300	48-380	47-1460	41-500	329
Total N (mg/l)	3.6-17	6-21	40-74	0.6-11	16
Total P (mg/l)	0.1- >49	0.1- >101	68-74	0.6 - > 68	9

High phosphorus load in greywater is attributed to the inclusion of laundry wastewater and to a lesser extent kitchen wastewater. Laundry detergents and dishwashing soaps contain high levels of phosphorus. In countries such as Sweden and Norway where phosphorus free detergents are used, one would expect a much lower phosphorus load in the greywater, *see* Table 2.1. It is evident that the phosphorus load in Sweden (9 mg/l) is considerably lower than the range of phosphorus load (0.1 – 101 mg/l) from the bathroom, kitchen and laundry presented from other countries by Donner et al. (2010). In Sweden, there is a legal ban on the use of phosphates in detergents for household use. However, the report by Jönsson et al. (2005) was published in the year 2005 (prior to the legal ban). Nonetheless the impact of discussions and campaigns for the use of phosphorus-free detergents around that time, could have impacted household consumption habits and thereby explaining the low P values in the raw household greywater in Sweden recorded in 2005.

2.2 Greywater discharge requirements

As mentioned earlier, GW is considerably less polluted than blackwater. This is based on the general understanding that fecal matter contains the majority of the microbial organisms and that urine has the highest composition of nitrogen compared to bathing, laundry and kitchen water. Nonetheless studies reveal the presence of *E.coli* in greywater which raises concerns for the need of further treatment to ensure that greywater is clean and safe for reuse (Larsen et al., 2013). The presence of *E.coli* in GW may be attributed to contamination with fecal matter. Some of the sources of this contaminations are; diaper changes, washing clothes and hands that contain fecal matter in the washing basins.

For the purposes of this thesis report, the word 'effluent' refers to the treated GW i.e. greywater that is clean, safe and ready for reuse. The greywater treatment method to be selected depends on the required effluent quality which in turn depends on the desired end use of the effluent. If greywater is to be used for flushing toilets, then it should be treated to a quality that does not favour algae growth and degradation of the piping system. If the effluent is to be used for irrigation or groundwater table recharge, then probably the N, P, turbidity and *E.coli* concentrations should be monitored so as not to cause eutrophication, microbial proliferation and high turbidity in water bodies. For example, if the effluent is to be discharged off to the sea, then it should be treated to a quality of water in the sea or better. The Oceanhamnen project is located at the harbor, with a possibility for discharge to sea after treatment. However, for the purposes of this thesis study, the anticipated greywater reuse at the Oceanhamnen project is recreational i.e. a water park.

2.2.1 EU bathing water quality regulation

The EU bathing water quality regulation categorizes bathing water quality based on four classifications, namely; poor, sufficient, good and excellent quality. For the purposes of this thesis, only the classifications 'good' and 'excellent' quality are deemed applicable for the Oceanhamnen area in Helsingborg. For a 'good' quality, the EU bathing water quality regulation recommends a maximum of 1000 colony forming units per 100 ml for inland waters and 500 colony forming units per 100 ml for coastal and transitional waters. For an 'excellent' quality, the EU bathing water quality regulation recommends a maximum of 500 colony forming units per 100 ml for inland waters and a maximum of 250 colony forming units per 100 ml for coastal and transitional waters (EU, 2008).

As mentioned above, the proposed project is located in close vicinity to the Helsingborg harbor. One could argue that the effluent falls categorically under both the inland waters and coastal and transitional water categories of the EU bathing water quality regulation. Therefore, the effluent must at the very least meet the maximum recommended EU bathing water quality *E.coli* concentrations. Table 2.2 presents an extract of the relevant recommended maximum *E.coli* concentrations for Helsingborg.

Table 2.2. An extract of the recommended maximum E.coli concentrations from the EU bathing water quality regulation that are relevant for Oceanhamnen.

Parameter	**'Excellent' quality**	**'Good' quality**
Inland waters		
Escherichia coli (cfu/100ml)	500	1000
Coastal and transitional waters		
Escherichia coli (cfu/100ml)	250	500

2.2.2 Drinking water regulation

The majority of greywater reuse from the literature is limited to flushing toilets and supporting aquatic and plant life. In the Oceanhamnen project, the reuse for the treated greywater is recreational i.e. a water park. In recreational areas such as water parks, aerosols are formed as a result of wind blowing through the water or from the spread of water if it includes a fountain. In aerosol form, pathogens and other microorganisms easily cling on water particles further increasing the risk for disease-spread when ingested (especially by children) or in contact with human body. (Barker and Jones, 2005). When water is circulated in the water park, the water is exposed to an open environment, which increases the chance for contamination. Sources of bacteria include people, animals (birds, pets and wild animals), soil particles and waste that enter into the water stream.

For the reasons stated above, once such a sensitive greywater reuse application is under consideration, the treatment method to be selected must be able to yield effluent of a quality close to that of drinking water quality requirements in order to minimize the spread of diseases and safeguard the health. This forms basis for the discussion of drinking water requirements.

Table 2.3. Table showing the Swedish drinking water quality requirements (Livsmedelsverket, 2001)

Parameter	**N (mg/l)**	**Turbidity (NTU)**	***E.coli* (cfu/100 ml)**
Swedish drinking water quality requirements	Nitrate - 50 (NO_3) Nitrite - 0.5 (NO_2)	0.5	100

Drinking water requirements are stringent compared to the requirements of other water standards. For example, the drinking water regulation requires a maximum *E.coli* concentration of 100 colony forming units per 100 ml (Livsmedelsverket, 2001) as compared to a maximum of 250 colony forming units per 100 ml for 'excellent' water quality required by the EU bathing water quality regulation.

2.2.3 WWTP discharge requirements

Wastewater treatment plants (WWTP) discharge requirements may be used when gauging the quality of treated effluent especially if the final step of the treatment process is discharge to a receiving water. WWTP handle mixed black and greywater; effluent from a WWTP is likely to have a much higher concentrations of pollutants such as N, P and BOD than effluent from an 'only' greywater treatment system.

Table 2.4. Table showing the discharge limits for Öresundsverket WWTP in Helsingborg. The N, P and BOD discharge limits were obtained from 'Miljörapport' (NSVA, 2016) on Öresundsverket.

Parameter	**N**	**P**	**BOD**
Units	mg/l	mg/l	mg/l
Öresundsverket WWTP discharge limits	10	0.5	10

2.2.4 Prevailing quality of the receiving waters

Another possible method for ensuring that effluent quality meets acceptable discharge requirements, could be to compare the effluent quality to that prevailing in the receiving waters. This would be a good substitute for areas where there are no guidelines or regulations for effluent discharge to the receiving water. In this case, one can conclude that if effluent quality is better or the same as the quality in the receiving water, the discharge is acceptable and if the effluent quality is lower than that of the receiving water, the treatment method selected is not efficient.

Table 2.5. A table showing the concentration ranges for P, N, TOC and Turbidity for lakes and water courses in Sweden (SEPA, 2000).

Parameter	**TN**	**TP**	**TOC**	**Turbidity**
Unit	mg/l	mg/l	mg/l	NTU
Low concentrations	< 0.3	< 0.0125	< 4	< 0.5
Very high concentrations	> 5	> 0.1	> 16	> 7

This water quality assessment method can only be applicable to the area in Helsingborg if discharge to sea is considered. However even then, the EU bathing regulations take precedence over prevailing quality of the receiving waters at the Helsingborg harbor.

3 Materials and Methods

This chapter aims to present and further elaborate on the general methodology presented in the section 1.5 of the report. A comprehensive literature review, two (2) site visits to greywater treatment pilot projects and consultations with some selected experts on greywater treatment were carried out throughout the thesis project. Even though a lot of the research interest in greywater treatment and consequently greywater reuse date back to roughly only a decade ago, a lot of reading material in greywater is now available. There was a need to exhaustively define the scope of the literature for the thesis to ensure that the thesis study meets the project aim and goal defined in section 1.4 of the report.

For example, the aim of this thesis is to suggest a suitable treatment of source separated greywater for discharge into an urban environment. However, there are a number of methods that have been used all over the world to efficiently treat greywater depending on the desired use of the treated effluent. This was achieved through the formulation of *selection criteria* in order to limit the literature review i.e. ensure that only relevant literature was reviewed. The selection criteria were chosen in such a way that it yields a close to perfect representation of the Oceanhamnen area in the city of Helsingborg. The site visits were also chosen based on the selection criteria. For example, the pilot projects in Berlin and Oslo are closely related to the proposed project in Helsingborg since all the cities experience cold climates, have a small area footprint and represent urban environments.

Once the treatment methods were selected using selection criteria, *evaluation criteria* were then used to evaluate how well the selected treatment methods meet the thesis aim of their applicable to the Oceanhamnen area.

3.1 Selection criteria

Based on the explanation above, the urban environment and climatic conditions are the two vital selection criteria for the Oceanhamnen area in city of Helsingborg.

3.1.1 Urban environment

Oceanhamnen is an area located in the city of Helsingborg. The selected methods should be appropriate for application to such an urban setting characterized by high population density, a lot of infrastructure and limited space. Because of limited space, treatment methods selected must have a relatively small area footprint (in practice meaning that wetland solutions and sedimentary basins were excluded).

3.1.2 Climatic conditions

Sweden experiences cold temperatures in the winter and warm temperatures in the summer. Since Oceanhamnen is located in Sweden, it was paramount to ensure that the treatment methods sought after were applicable to such temperature ranges. Some treatment methods found in the literature were tried and tested in only tropical climates and caution had to be taken to ensure there was other supporting criteria (such as from above) before such methods were selected.

3.2 Evaluation criteria

The evaluation criteria included; i) Size (capacity) of the reference implementations, ii) Footprint iii) Effluent quality, iv) Reliability of the reference implementations.

3.2.1 Size (Capacity)

Size represents the capacity of reference implementations i.e. the capacity of previous projects (usually expressed as the number of persons served) where the selected methods have been used. The size was compared to that of the Oceanhamnen project, which is anticipated to serve an estimated 2000 persons.

3.2.2 Footprint

Footprint is the area occupied by the project. The Oceanhamnen area is located in the city centre and close to the harbor at Helsingborg. This means that there is limited space and therefore treatment systems that have a low footprint are preferred.

3.2.3 Effluent quality

The method selected should be able to meet effluent quality requirements as stipulated in applicable regulations. Considering that the intended final treated greywater effluent re-use is for recreational purposes (i.e. a water park), it is paramount that the treated effluent meets the bathing water or the Swedish drinking water quality since there is human body contact and a high likelihood of consumption of the water. For the purposes of this thesis, comparisons have been based on the EU bathing standards, Swedish drinking water standards, effluent discharge limits for the local WWTP (Öresundsverket). However, the EU bathing water and the Swedish drinking water quality regulations take precedence over the WWTP discharge limits. Also, the effluent quality is assessed based on only the Nitrogen (N), Phosphorus (P), BOD, Turbidity and *E.coli* concentrations because they significantly affect the quality of the treated greywater but more importantly *E.coli* is the main parameter for assessment of effluent to EU bathing regulations and the Swedish drinking water quality requirements.

3.2.4 Reliability

Treatment methods that have been successfully applied in more than one area and for longer periods of time are deemed more reliable since there is evidence of previous successful applications.

Treatment methods tried and tested in full or large scale application are likely to be more reliable compared to those that have only been tested on a laboratory scale.

3.3 Literature review

The literature review utilized several accessible databases including LUBsearch, Google scholar, ScienceDirect and Scopus. Table 3.1 presents an overview of databases and keywords used during the literature study. A technical description of information on treatment methods obtained from the review is presented in Chapter 5 of the report.

Table 3.1. A table showing an overview of the main databases and keywords used throughout the course of the literature review. The aim of the table is to further elucidate how the literature study was undertaken but does not exhaustively present all the searches made during the entire course of the thesis.

No.	Databases	Search strategy	Hits
1	Scopus	“greywater" OR “graywater" OR “grey water" OR “gray water"	1677
		“greywater" OR “graywater" OR “grey water" OR “gray water" AND “Source separation”	34
		“greywater" OR “graywater" OR “grey water" OR “gray water" AND “Source separation” AND “Urban areas”	10
		"greywater” OR ”greywater” AND "Reclamation” AND “Treatment methods”	2
		Greywater Reclamation	148
3	Google Scholar	Greywater treatment systems	22400
4	LUBsearch	Greywater treatment methods	308

An initial open database search on greywater and greywater treatment systems yielded up to as many as 22400 hits. Not all the literature from the hits, Table 3.1 was relevant to the thesis study. A further literature search using the formulated selection criteria based on the urban environment and climatic conditions limited the review and yielded more representative literature to the Oceanhamnen area and is presented in Chapter 5 of the report.

3.4 Site visits

Site visits to existing greywater treatment systems were carried out to supplement the literature study. A total of three site visits were undertaken during the course of the thesis project. The first site visit was a visit to the Oceanhamnen city district currently under construction in the city of Helsingborg and its surroundings. This visit was carried out to gain a better understanding of the location and scale of the project. The second and third site visits were visits to pilot greywater treatment systems at the Roof Water Farm in Berlin, Germany and at Klosterenga in Oslo, Norway. The projects are located in the centres of Berlin and Oslo cities respectively and therefore were envisioned to give a perfect representation of an urban environment with respect to Helsingborg.

An interview visit to Folke Günther, a pioneer of source separation in Sweden was also done. Günther was also involved in the design and operation of a representative greywater treatment system in Sweden, the greywater system at Kalmar University College.

Lastly, a number of consultations were also carried out via email and telephone. The consultations targeted researchers and organizations that are involved or that run projects with a component of greywater treatment in order to obtain further relevant information to the thesis study.

The information obtained from the methods described above is presented and discussed in the result section of the report.

4 Site visits

As earlier mentioned in the chapter 3 (Materials and Methods) of the report, site visits to Berlin (Roof water farm) and Oslo (Klosterenga) cities were undertaken during the course of the thesis. The findings from the two studies are discussed in the subsequent sections below.

4.1 Roof Water Farm (RWF)

4.1.1 Location

The Roof water farm is located in Berlin, Germany. The study area consists of a greywater treatment facility (located indoors), a constructed wetland, a greenhouse and “Block 6” (a 3-4 storeyed building served by the greywater treatment facility) consisting of 71 flats with 250 people.

4.1.2 Description of the GW treatment system

The building consists of separate piping to facilitate source separation where the greywater is led to the greywater treatment facility and the blackwater to the central treatment facility. The treatment facility is designed for and receives 10 m^3 per day of greywater and the excess greywater (> 10 m^3) is directly discharged to the municipal sewer network (Nolde et al., 2016).

The greywater received is treated and recycled onsite for use in toilet flushing and home gardening. Some of the recycled water is used for growing food and fish (there is an aquarium inside the greywater treatment building). The activities undertaken at the roof water farm follow the overview in Figure 4.1. The activities enclosed by the blue outline are the only activities relevant to the thesis study. It is important to mention that rainwater is treated in the constructed wetland and not mixed with the greywater from Block 6.

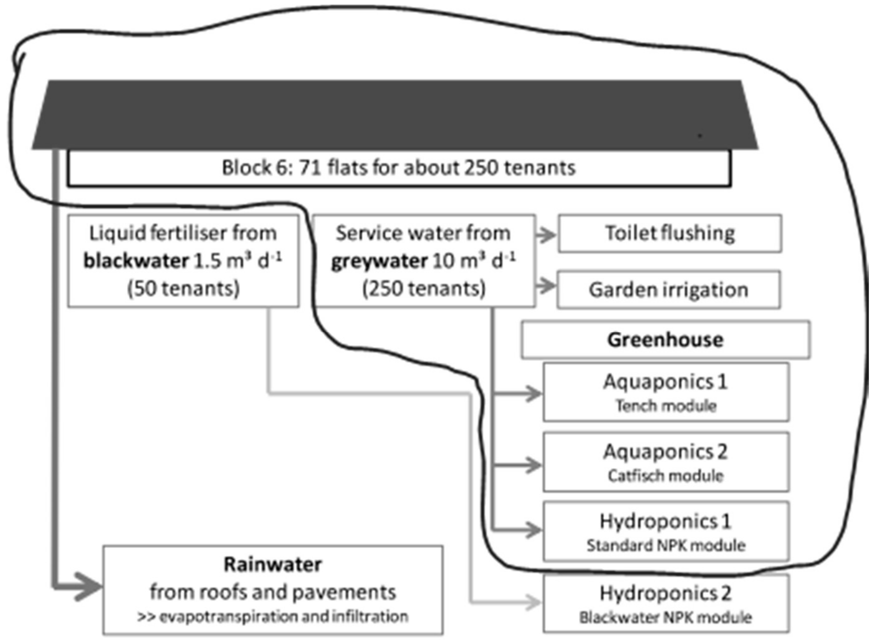

Figure 4.1. Overview of Roof water farm activities (Source: Nolde et al., 2016 modified by the author). Published with permission from Erwin Nolde.

The greywater is pumped to the greywater treatment system housed in a small timber-constructed house, a few metres from Block 6, *see* Figure 4.2. The greywater undergoes treatment using a multi-stage Moving Bed Biofilm Reactor (MBBR). The system consists of 10 Polyethylene tanks (in series), *see* Figure 4.4; each having a capacity of 1.4 m^3 and designed for a daily flow of 10 m^3 of greywater.

Figure 4.2. A photo of the small timber structure housing the MBBR GW treatment system. Photo by the author.

One of the aims of the Roof Water Farm project is to treat greywater without the use of chemicals. Foam cubes are used in this system; they are placed inside the tanks and house the bacteria (the bacteria lives on the surface of the foam cubes). There are different types of bacteria in the different stages of the system, for example in the first stage, the bacteria present is thought to be fat consuming bacteria (Nolde and Arinaitwe, 2018).

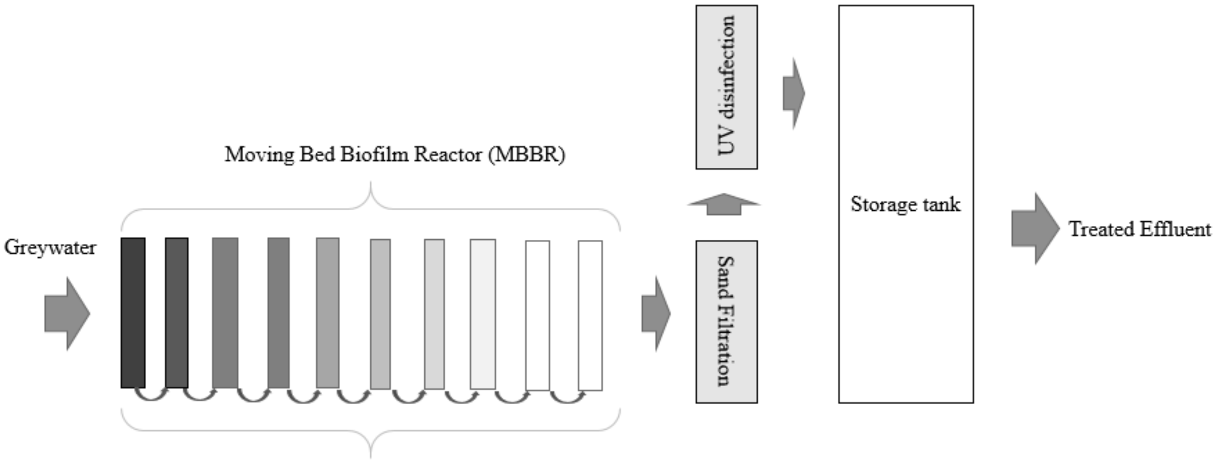

Figure 4.3. A process scheme showing water flow in the greywater treatment. Reproduced from Water Science & Technology 76 (12) 3328-3339, with permission from copyright holders, IWA Publishing.

The quality of the water increases along the treatment process, see Figure 4.3. The water in the first tanks is very polluted (high turbidity) as can be clearly observed by the naked eye, the water gets clearer along the different tanks (less turbidity observed) and in the last tanks the water is very clear. The water is further passed through sand filtration and UV radiation for disinfection. The resulting effluent is circulated back to the houses for toilet flushing and home gardening, fish farming (aquarium) and plant growing is another use of the treated greywater. The greywater treatment system has not undergone any infrastructure maintenance since inception (2006) and it depicts high operational stability (Nolde et al., 2016).

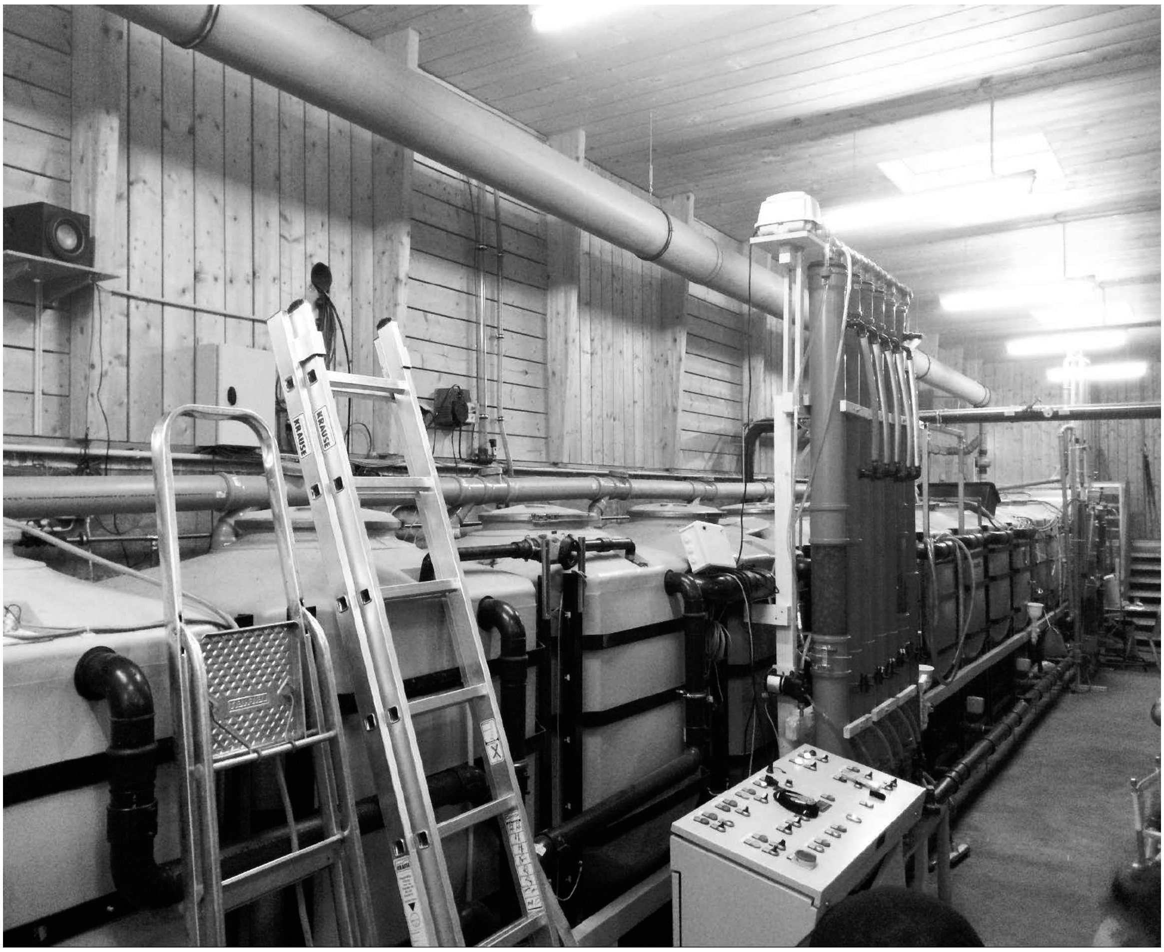

Figure 4.4. A photo of the polyethylene tanks (10 tanks in series) that form part of the MBBR treatment system. Photo by the author.

4.1.3 Effluent quality

Different tests have been carried out on the treated GW effluent from the MBBR systems (Saidi et al., 2017; Nolde et al. 2016). Results of the effluent quality obtained and the initial influent GW into the MBBR are presented in Table 4.1 together with influent and effluent quality in the municipal WWTP treatment plants in Berlin for comparison.

Table 4.1. A table showing the average composition of the greywater influent and effluent from greywater treatment (MBBR) system together with a comparison to the composition of influent and effluent in the municipal WWTP in Berlin (Nolde et al., 2016). An extra column was added to show results obtained from a more recent sampling of the same MBBR system for an average treatment performance of 10 settled samples (Saidi et al., 2017).

Parameter / Unit		**Greywater treatment (Roof water Farm)** (Nolde et al., 2016)		**Municipal WWTP Berlin** (Nolde et al., 2016)		**Greywater** (Saidi et al., 2017)	
		Influent	Effluent	Influent	Effluent	Influent	Effluent
Turbidity	NTU		< 1				
BOD_5	mg/l	460	< 5	218	3.8	293 (BOD_7)	1.6
Total N	mg/l	16.2		72		13	4.8
NH_4-N	mg/l	2.7	< 0.03	45	0.9	7.15	0.02
NO_3-N	mg/l		3.5		6.9	0.034	3.27
Total P	mg/l	4.7		16	0.3	2.81	2.42
E.coli	CFU/100 ml	7.5×10^5 - 1.4×10^6	2-3		10^4 - 10^5		

From Table 4.1, it is evident that the MBBR treatment system at Roof Water Farm (RWF) attains high organic removal rates. Two studies on the system by Nolde et al., 2016 and Saidi et al., 2017, show that the MBBR systems achieves organic removal rates of 94.5 % (COD) and 99.4 % (BOD). The influent to the MBBR system contains 13 mg/l (N), a relatively low value which may be attributed to the absence of urine in greywater. The effluent contains 4.8 mg/l (N) which is only a 64% reduction after treatment. This means that the MBBR system is not very efficient in N removal.

Even for countries where detergents must be phosphorus (P) free, greywater influent contains phosphorus since P may result from food. In Table 4.1, the phosphorus (P) removal is extremely low, almost non-existent. The MBBR system at the RWF attains a significantly low P reduction of only 14%. Phosphorus removal often requires chemical precipitation to attain higher removal rates (Gillberg et al., 2003). The MBBR system at the RWF does not use any form of chemical treatment and this could explain the low P removal rates.

In regards to pathogens, the effluent from the MBBR system is used for toilet flushing and irrigation of garden according to the EU bathing quality regulation. The MBBR system at RWF achieves less than 10 colony forming units *(E.coli)* per 100 ml which is within the EU bathing water quality regulation recommendation for a maximum of 1000 colony forming units (*E.coli)* per 100 ml for inland waters ('good quality'). Considering that the influent was very polluted i.e. with high turbidity that was visible to the naked eye, the MBBR system achieves a significantly low effluent turbidity of < 1 (NTU). This may be attributed to the presence of the microbial biofilms which consume the organic matter in the greywater, thereby making the MBBR system efficient in the removal of organic matter.

Comparing the effluent quality of the MBBR system at the RWF and the municipal wastewater treatment plants in Berlin, the MBBR attains higher removal rates for BOD, COD (organic removal) and *E.coli* than the WWTP. However, the WWTP achieves higher removal rates for P than the MBBR system which can be attributed to the use of chemical precipitation. The professionals of the Roof Water Farm (RWF) site visited in Berlin, suggested that greywater after treatment can be suitable for drinking, however no tests have been done to support this (Nolde and Arinaitwe, 2018). Currently, greywater has only been successfully reused for flushing toilets and supporting aquatic and plant life (Nolde et al., 2016). The EU bathing water quality regulation is used for assessment of effluent quality at RWF for reuse.

4.2 Klosterenga

4.2.1 Location

The site is located in Klosterenga in Oslo, Norway. The pilot greywater treatment system services around 100 persons living in an apartment block that is fitted with source separation. The treatment system was built in the year 2000 and is located in the courtyard of the apartment building. Source separation allows for the less polluted greywater to be separated from the more polluted blackwater at the source.

4.2.2 Description of the GW treatment system

Greywater from the apartment building is pre-treated in the septic tank before further pumped into the vertical flow aerobic biofilters. From the biofilters, the water flows through two distribution pipes by gravity into the subsurface horizontal single flow constructed wetland porous media filter, as depicted in Figure 4.5.

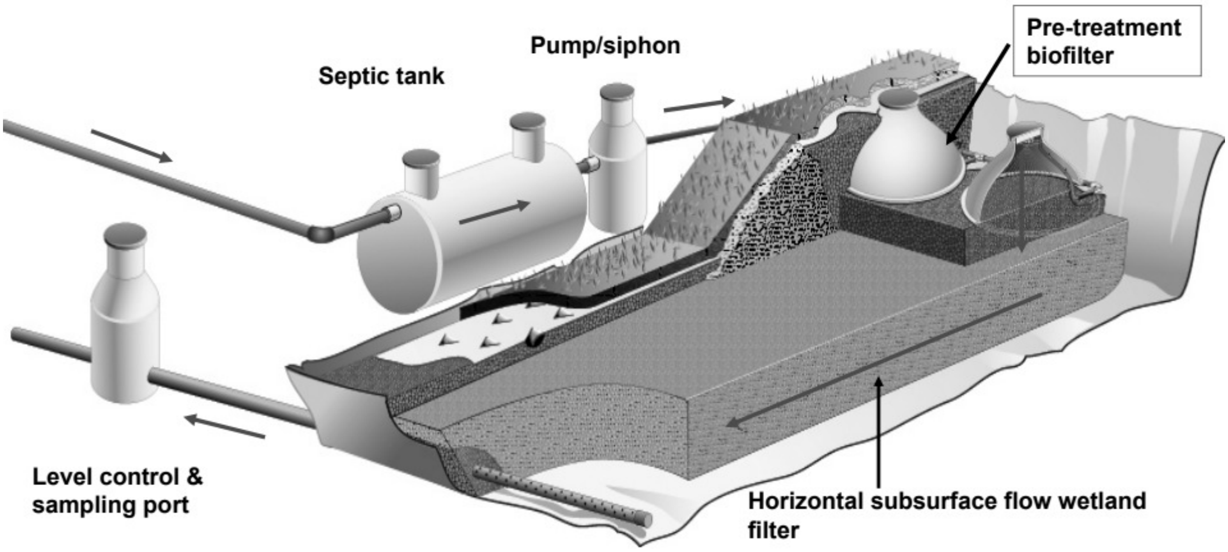

Figure 4.5. Overview of the greywater treatment system at an apartment building at Klosterenga in Oslo, Norway (Jenssen, 2005, Jenssen & Vråle, 2004). Published with permission from Petter Jenssen.

The wetland is enclosed in a concrete basin, has a depth of 1.8 m with subsurface flow to eliminate any effect from cold winters; the wetland has an area of 110 m^2. The wetland filter has varying grain sizes. Water is flowing through the larger grain sizes at one end to smaller grain sizes at the extreme end of the wetland. After the filter, the water is pumped to a waterfall in the courtyard for recreational purposes, and after that discharged into the municipal sewer system. The system has a footprint of 1.5 m^2 /person, of which, ⅓ is occupied by the biofilters; there are 10 biofilters.

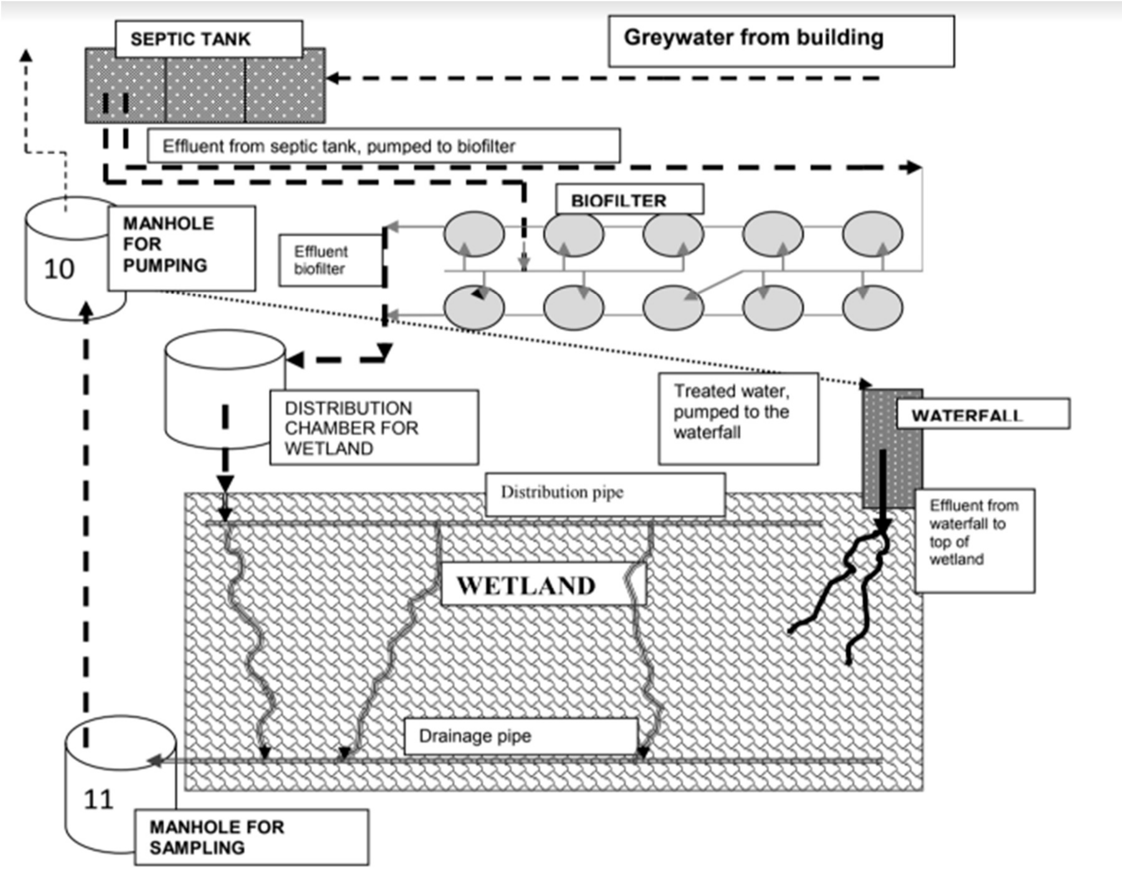

Figure 4.6. A schematic of the greywater treatment system at Klosterenga, Oslo. Manhole 11 is the sampling point, from which water can also be drawn out of the system after treatment by the wetland. From manhole 11 water flows by gravity to Manhole 10, from which it is pumped to the waterfall before it joins the municipal sewer system (Sagen, 2014). Published with permission from Petter Jenssen.

4.2.3 Effluent quality

The greywater treatment system at Klosterenga consistently yields good quality effluent concentrations as shown in Table 4.2 (Jenssen, 2005).

Table 4.2. A table showing the effluent concentration after treatment in the system at Klosterenga, Oslo (Jenssen, 2005).

Parameter	TN (mg/l)	TP (mg/l)	BOD (mg/l)	COD (mg/l)	*E.coli* (CFU/100ml)
GW Effluent	2.5	0.03	5	19	0

From Table 4.2, it is evident that the combined biofilter and constructed wetland (CW) system at Klosterenga yields excellent effluent quality with significantly low N, P, BOD and *E.coli* concentrations. Significantly high P and *E.coli* reduction may be attributed to the presence of the light weight expanded clay aggregate (FiltraliteP) which has very high phosphorus sorption and bacteria reduction capabilities (Jenssen & Vråle, 2004; Jenssen, 2005; Jenssen and Arinaitwe, 2018). Some of the phosphorus is also consumed by the plants as the water passes through the constructed wetland. The long retention time achieved in the constructed wetland stage could also explain the excellent effluent quality.

The effluent water is used for garden irrigation, is discharged into the apartment's compound (during summer periods) before final discharge into the municipal sewer system. The effluent from the combined biofilter and CW system is reused according to the EU bathing quality regulation. The treatment systems achieves less than 0 colony forming units *(E.coli)* per 100 ml which is within the EU bathing water quality regulation recommendation for a maximum of 1000 colony forming units *(E.coli)* per 100 ml for inland waters ('good quality'). The system yields a low N effluent concentration (2.5 mg/l) which is less than the recommended maximum value (10 mg N/l) for drinking water quality by the World Health organization (WHO, 1993).

5 Greywater treatment in urban environments

This chapter presents a summary based on a comprehensive literature study on greywater and treatment methods applicable in urban environments.

5.1 Greywater treatment methods

A greywater treatment system choice depends on the GW effluent quality required and its intended reuse application. As highlighted in Chapter 3 (Materials and Methods), section 3.3 of the report, a comprehensive literature search from some of the available databases such as Google scholar, SCOPUS and LUBsearch was done. Different search strategies were used to obtain the greywater treatment methods which are presented in Table 5.1.

Table 5.1. A table showing an overview of the tools (databases, search strategy and number of hits) used during the thesis to obtain the relevant literature on greywater treatments. The greywater treatment methods presented in the table are the ones that were most common in the searches.

No	Databases	Search strategy	Hits	Relevant hits
1.	SCOPUS	"Greywater treatment" OR "graywater treatment" OR "grey water treatment" OR "gray water treatment" AND "rotating biological contactor"	2	1
	Google scholar	Treatment of greywater using rotating biological contactor in urban areas	929	10
	LUBsearch	Rotating biological contactor and greywater treatment	8	3
2.	SCOPUS	"Greywater treatment" OR "graywater treatment" OR "grey water treatment" OR "gray water treatment" AND "moving bed biofilm reactor"	2	2
	Google scholar	Treatment of greywater using moving bed biofilm reactor in urban areas	558	6
	LUBsearch	Moving bed biofilm reactor in greywater treatment	12	12
3.	SCOPUS	"Greywater treatment" OR "graywater treatment" OR "grey water treatment" OR "gray water treatment" AND "membrane bioreactor"	21	15
	Google scholar	Treatment of greywater using membrane bioreactor in urban areas	2,330	10
	LUBsearch	Membrane bioreactor in greywater treatment	122	44
4.	SCOPUS	"Greywater treatment" OR "graywater treatment" OR "grey water treatment" OR "gray water treatment" AND "constructed wetlands "AND "Urban areas"	2	2
	Google scholar	Treatment of greywater using constructed wetlands in urban areas	9,130	9,100
	LUBsearch	Greywater treatment using constructed wetlands	48	40
		Constructed wetlands in greywater treatment	190	150

Table 5.1 confirms that not all the literature obtained was relevant to the Oceanhamnen area. The selection criteria (urban environment and climate conditions i.e. cold climate) were then applied to obtain the relevant hits. From the relevant hits, some of the case studies, *see* Table 5.2, involving the most common relevant greywater treatment systems obtained from literature search are described in sections 5.1.1 to 5.1.4 of the report. It is important to note that construction wetlands yielded the most hits. However, for the purpose of this thesis, utilization of a constructed wetland to treat greywater in the Oceanhamnen area is challenging due to limited space. Nonetheless a representative greywater case study at Kalmar Technical high school was selected and described in section 5.1.4 of the report. This particular case study was included because of its location (i.e. Sweden) rather than the possibility of its successful implementation in the Oceanhamnen area.

Table 5.2. Table showing some of the case studies obtained from the literature based on the selection criteria.

GW treatment method	Case study location	Reference
Rotating Biological Contactor (RBC)	Technon campus, Israel	Friedler et.al., 2005
	Berlin, Kreuzberg, Germany	Nolde, 2000
Moving Bed Biofilm Reactor (MBBR)	Arnimplatz, Berlin	Nolde et al., 2014
	RWF, Berlin	Nolde et al., 2016
Membrane Bioreactor (MBR)	Technon campus, Israel	Friedler et al., 2005
	Berlin-Stahnsdorf WWTP site	Lesjean & Gnirss, 2006
Biofilters & Constructed Wetlands	Klosterenga, Oslo	Jenssen et al., 2010
	Kalmar, Sweden (only constructed wetland)	Günther, 2000

5.1.1 Rotating Biological contactor (RBC)

Case study 1: A pilot greywater treatment study at Technon Campus, Israel

An RBC treatment system was used in combination with sand filtration (SF) followed by disinfection by chlorination in order to treat greywater at a pilot greywater treatment study at Technon Campus in Israel. The effluent from the RBC system was used for toilet flushing. The

RBC system serves an 8-storey building (6 flats per storey), that houses married students (some with young children) at Technon campus (Friedler et al., 2005).

After screening, raw wastewater passes through the Equalization basin (EB) whose purpose is to regulate the flow through the treatment system. The water then undergoes biological treatment in the RBC system. The water passes through the Sedimentation Basin (SB) after the RBC, sludge is removed at this stage. The Pre-filtration storage tank (PFST) serves as a storage (st.) tank in order to regulate SB effluent flow and the Sand Filtration (SF) influent flow. The water is filtered by a gravity filter in the SF stage and then disinfected using chlorine before it is reused for toilet flushing (Friedler et al., 2005). A schematic of the layout of the pilot treatment system is shown in Figure 5.1.

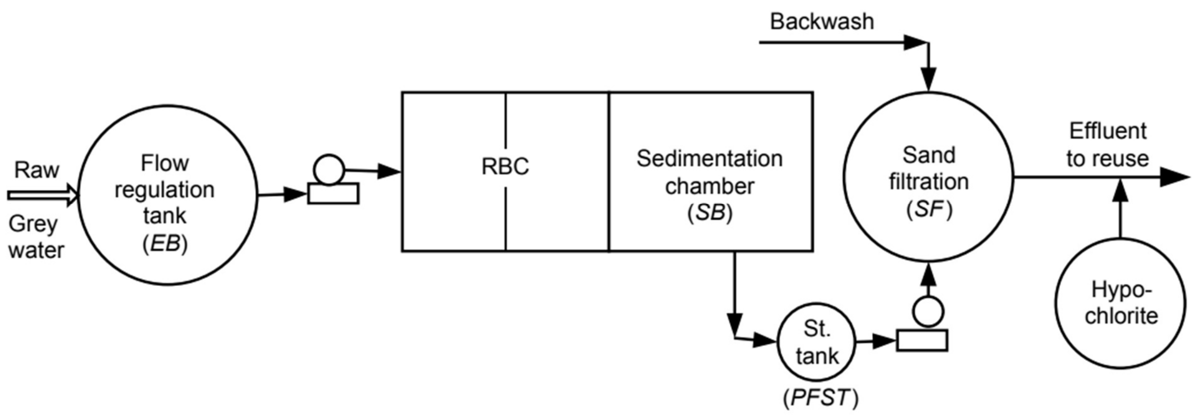

Figure 5.1. Schematic of the RBC system used in a pilot greywater treatment study at Technon Campus, Israel (Friedler et al., 2005). Reproduced from Water Science & Technology 51(10) 187-194, with permission from copyright holders, IWA Publishing.

To establish the efficiency of the RBC system in the treatment of GW, water quality tests were carried out on samples collected twice a week at different sampling points over a period of seven months (Friedler et al., 2005, Friedler et al. 2006). In Table 5.3, it can be seen that the RBC system in combination with sand filtration achieves high BOD, *E.coli* and Turbidity removal rates of 96 %, 100 % and 98 % respectively. It is evident that disinfection plays a significant role in reduction of *E.coli* in greywater. The treatment system also achieved fairly high N removal rates (87 %). The RBC system shows less efficiency in removing P from greywater with the treatment system able to achieve only 58 % P removal rate. It is also evident from Table 5.3 That most of the greywater components were removed by the biological treatment i.e. the RBC stage.

Table 5.3. A table summarizing the greywater effluent quality and removal efficiencies of the RBC system at the Technon Campus, Israel (Friedler et al., 2005). n represents the number of samples analyzed. SB =Sedimentation chamber, SF = Sand filtration.

Parameter	Raw GW	RBC + SB	RBC + SF	Disinfection (after 0.5h)	% removal
TP (mg/l)	4.8		2		58 %
TN (mg/l)	8.1		1		87 %
BOD (mg/l)	59 (n = 17)	6.6 (n = 13)	2.3 (n = 11)		96%
E.coli (CFU/100 ml)	5.6×10^5 (n = 16)	2.9×10^3 (n= 16)	5.1×10^4 (n= 16)	0.1	100%
Turbidity (NTU)	33 (n = 31)	1.9 (n = 32)	0.61 (n = 24)		98%

5.1.2 Moving Biofilm Bed Reactor (MBBR)

Case study 2: Multi-storeyed passive residential building in Berlin, Germany

Another application of a similar MBBR (followed by UV disinfection) system to treat greywater successfully is being used in a passive residential storeyed building (Nolde et al., 2014). 41 flats containing 123 persons and 4 commercial units are connected to the treatment system. The treated effluent is used for toilet flushing. Analysis of final effluent from the MBBR system show BOD concentration of < 5 mg/l and Turbidity of < 2 NTU (Nolde et al., 2014). The greywater recycling system also comprises of a heat recovery unit where heat is recovered from greywater by use of heat exchangers (Nolde et al., 2014).

Case study 3: Roof water farm in Berlin Germany

At the Roof water farm, the MBBR treatment system is used to treat greywater from Block 6, a residential building serving about 250 persons. The effluent from the MBBR system passes through sand filtration and UV disinfection before circulating for toilet flushing, garden irrigation and fish farming on the roof water farm (Nolde et al., 2016).

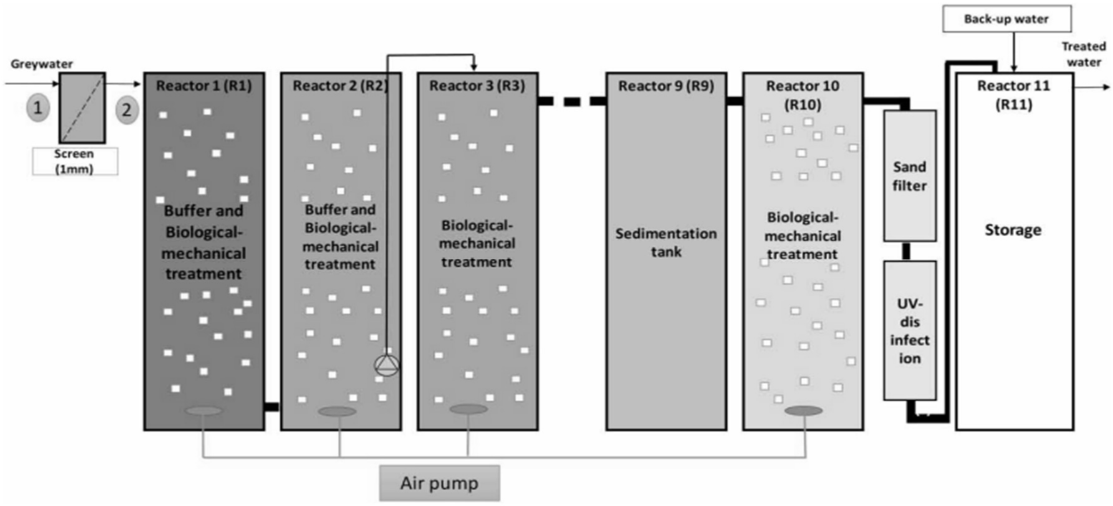

Figure 5.2. A simple schematic of the MBBR system used at the Roof Water Farm in Berlin, Germany (Saidi et al., 2017). Reproduced from Water Science & Technology 76 (12) 3328-3339, with permission from copyright holders, IWA Publishing.

5.1.3 Membrane Bioreactor (MBR)

MBR can serve similar purposes as activated sludge systems, with membrane filters instead of secondary clarifiers.

Case study 4: Sanitation Concept for Separate Treatment" (SCST), Berlin Germany

The SCST was a demonstration project run by the Berlin Competence Centre for Water and the Berliner Wasserbetriebe. Ten private apartments and one office, amounting to approximately 50 persons were connected to the SCST scheme (Lesjean and Gnirss, 2006). An MBR system was used to treat the greywater from bathrooms and kitchens for a period of over 8 months. The N and P concentrations in the influent and effluent are presented in Table 5.4 (Lesjean and Gnirss, 2006).

Table 5.4. Table showing the raw greywater composition and the effluent concentration after treatment by the MBR system (Lesjean and Gnirss, 2006).

Parameter	Total P	Total N	COD
Units	mg/l	mg/l	mg/l
Raw greywater	7.4	21	493
MBR effluent	3.5	10	24
% Removal	53 %	52 %	95 %

The MBR system did not achieve significant P and N removal rates, only 53 % and 52 % of the P and N in the raw greywater was removed respectively. The MBR system however achieved significant high COD removal rates of roughly 95 %. A comparison for phosphorus removal between the MBR (Table 5.4) and MBBR (Table 4.1) systems shows that both systems do not attain high P removal i.e. 53 % and 14 % respectively.

Case study 5: A pilot greywater treatment study at Technon Campus, Israel

The pilot greywater treatment study at Technon campus, Israel in section 5.1.1 was also operated using an MBR system. The RBC system in Figure 5.1 was replaced with an MBR system. The greywater was biologically treated in the MBR before disinfection. The results from effluent quality tests carried out on several samples after disinfection (Friedler et al., 2006) are presented in the Table 5.5.

Table 5.5. A table summarizing the greywater effluent quality and removal efficiencies of the MBR system at the Technon Campus, Israel. The table also shows results for an RBC system and sand filtration (similar to the one described in section 3.3.1) that was run simultaneously with the MBR system with similar raw greywater (Friedler et al., 2006).

Parameter	**Raw GW**	**MBR**	**Disinfection (after 0.5h)**	**% removal**	**RBC + SF**	**% removal**
BOD (mg/l)	69	1.1		98 %	1.8	97 %
E.coli (CFU/100 ml)	5.6×10^5 (n =31)	27 (n = 26)	0	100 %	4.8×10^4 (n=25)	86 %
Turbidity (NTU)	65	0.2		> 99 %	0.6	99 %

According to Table 5.5, the MBR treatment system attained maximum removal rate of 100 % for E.coli after disinfection. The RBC system with sand filtration on this same site only achieved 86 % E.*coli* removal for the same raw greywater influent. The MBR system also achieved significantly high BOD removal rate of 98 % similar to that achieved in the RBC system for the same site and greywater influent.

5.1.4 Constructed Wetlands

Case 6: Kalmar University, Sweden

A wetpark at the Technical University college of Kalmar, south Sweden was constructed in 1995-96 and served 500 students. The lightly polluted greywater from the building was purified in the wetpark and then reused in the building for dish and hand washing (Günther, 2000). The rain water from the building was also discharged into the wetpark. The layout of the wetpark is shown in Figure 5.3.

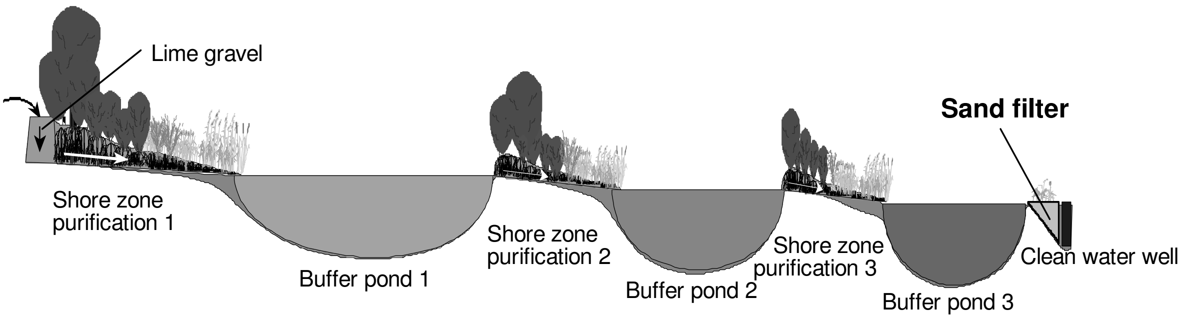

Figure 5.3. Layout of the wetpark at Kalmar University College (Günther, 2000). Published with permission from Elsevier.

The water passes through a lime-gravel surface to facilitate reduction of the organic matter by aerobic bacteria. After the lime-gravel stage, water then flows through the planted vegetation and is stored in the ponds before being fed into the consecutive zone. The process is repeated three times allowing for significant reduction in pathogens, BOD and N and nutrients (Günther, 2000). Water leaving the last pond is further treated using a sand filter system before collection in a well.

The wetpark area requirement was 1200 m^2 (about 40 m^2 per person). Such large space requirements make constructed wetlands unsuitable for dense urban areas such as the Oceanhamnen area. The wetpark systems allows for a long turnover time, coupled with a slow water flow through the system and the long underground passage; the system achieved significant reduction of bacteria and viruses in the effluent.

From Table 5.6, it can be observed that the constructed wetland at Kalmar University yielded high BOD, *E.coli* and P removal rates of 100 %, > 99 % and 94 % respectively. The wetland only achieved 57 % Nitrogen removal rate. The high removal rates for BOD, P and *E.coli* could be attributed to the long retention period in the water pond system and phosphorus consumption by the plants in the wetland (Günther, 2000).

Table 5.6. Table showing a comparison between average greywater influent concentrations into the wetpark and effluent N, P, BOD and E.coli concentrations after purification by the wetpark at Kalmar University College. n is the number of samples analyzed. The samples for the effluent concentrations results presented in the table were taken from the clean water well/reception well (Günther, 2000).

Parameter	**N**	**P**	**BOD**	***E.coli***
Unit	mg/l	mg/l	mg/l	cfu/100 ml
Greywater into wetpark	3.7 (n=6)	3.7 (n=6)	47 (n=14)	35 848 (n=13)
Effluent from wetpark	1.6 (n=5)	0.2 (n=5)	0 (n =9)	43 (n=9)
% Reduction	57 %	94 %	100 %	> 99%

Case 7: Constructed wetlands and aerobic biofilters

Filter beds have been successfully used in the Nordic countries (i.e. Denmark, Finland, Norway and Sweden) with at least nine found references of applications of filter beds (3 bed in Norway, 2 in Denmark, 1 in Sweden and 1 in Finland) constructed (Jenssen et al., 2010). The treatment system consists of; a septic tank, a pump well, a vertical flow single pass aerobic biofilter, a subsurface horizontal flow filter and an outlet well. The overview is shown in Figure 5.4.

Jenssen et al. (2010) describes treatment system as consisting of a septic tank followed by aerobic pre-treatment biofilter and a subsequent saturated flow grass-covered filter. Saturated filters contain Filtralite P, a light-weight expanded clay aggregate possessing high phosphorus sorption capacity (Jenssen et al., 2010). Jenssen et al. (2010) further suggests that filter beds are similar to subsurface flow constructed wetlands with pre-treatment bio filters, although they do not have wetland plants with roots submerged into the saturated filter.

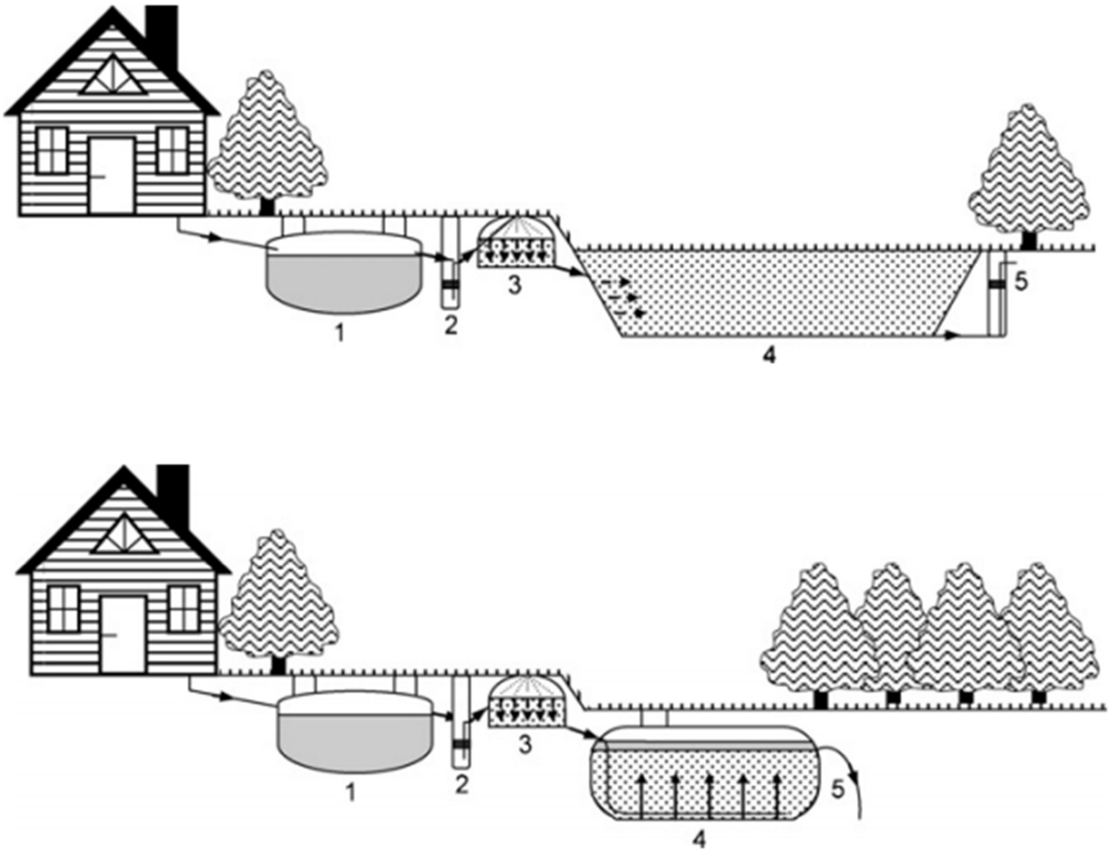

Figure 5.4. Top: General layout of the filter bed system: 1 – septic tank, 2 – pump well, 3 – aerobic biofilter, 4 – subsurface horizontal flow filter bed, 5 – outlet well. Bottom: Layout of the Norwegian compact filter system: 1 – septic tank, 2 – pump well, 3 – aerobic biofilter, 4 – upflow saturated filter tank, 5 – outlet (Jenssen et al., 2010). Published with permission from Elsevier.

In Norway, a combination of the aerated biofilters and constructed wetland has been successfully used for greywater treatment at Klosterenga (33 apartments), Torvetua (42 condominiums) and at Kaja plant which treats greywater from student dormitories at the Agricultural University of Norway. A comparison of the effluent results obtained at the three sites (Klosterenga, Torvetua and Kaja) are presented in Table 5.7 (Jenssen & Vråle, 2004).

Table 5.7. Table showing effluent concentrations at each stage of the combined aerated biofilter and constructed wetland treatment system (i.e. septic tank, biofilters and constructed wetland) at Kaja greywater treatment plant. n is the number of samples analyzed at Kaja plant. The table also presents the effluent concentrations at Torvetua and Klosterenga (KL.) in Norway (Jenssen & Vråle, 2004). All the three sites use a similar treatment method.

Parameter	**Kaja plant** (n = 11)						**KL.**	**Torvetua**
	Septic tank outlet	Biofilter outlet	CW outlet	% removal				
				Biofilter	CW	Biofilter & CW		
TP (mg/l)	0.97	0.32	0.07	67 %	78 %	93 %	0.03	0.21
TN (mg/l)	8.2	5.0	2.5	39 %	50 %	70 %	2.5	2.2
BOD (mg/l)	130.7	38.2	6.90	71 %	82 %	95 %	5.0	5.5
E.coli (cfu/100 ml)	106	10^3-10^5	0 – 10^3				0	< 1000

From Table 5.7, it can be clearly seen that the combined biofilter and constructed wetland system yields significantly high BOD and P removal rates, 95% and 93% respectively. The system also achieves significant reductions in *E.coli* concentrations to < 1000 colony forming units per 100 ml which lies below the maximum value (1000 colony forming units per100 ml) stipulated by the EU bathing water quality regulation for inland waters. The high removal rates for P and *E.coli* are attributed to the presence of Filtralite P, a light-weight expanded clay aggregate possessing high phosphorus sorption capacity and bacteria reduction capabilities. The treatment system only achieves 70 % N removal at Kaja plant.

From Table 5.7, it is evident that the constructed wetland removes a higher percentage of BOD (82 %) and P (78 %) compared to the biofilters that removes 71 % (BOD) and 67 % (P). This may be attributed to the long retention hours in a constructed wetland compared to a biofilter. Also, presence of the light weight aggregate in the constructed wetland improves the P removal efficiency. Both the constructed wetland and biofilter are not efficient at removing N with removal rates of 50 % and 39 % respectively. The combined treatment system of biofilters and constructed wetlands achieves higher removal efficiency for all parameters, BOD, N, P and *E.coli*. Comparing the effluent results from all the three sites in Table 5.7, all the respective results obtained are closely similar.

5.2 Water - energy nexus & thermal energy recovery from greywater

"Energy-water nexus refers to the interdependence between these two valuable resources, in that water is required to generate energy and energy is required to supply and treat water" (Malinowski et al., 2015).

Drinking water and wastewater treatment systems demand energy. While the majority of the energy consumed in drinking water systems is attributed to the pumping and distribution systems, the energy demand in wastewater systems is attributed to the influent loading and consequently the required treatment regime (Jeonga et al., 2017).

Greywater treatment consumes energy: The amount of energy consumed depends on the influent loading, the desired effluent quality, effluent reuse application and consequently the treatment method used. In turn, reusing greywater as a supplement to the drinking water supply for flushing toilets, irrigation, car washing, etc. reduces the overall pumping and distribution energy costs for drinking water demand. Energy is of course consumed in the distribution of the treated greywater to the point of reuse.

Case study: Passive residential building (Berlin, Germany)

Greywater treatment offers a sustainable source of thermal energy (Nolde et al., 2014). The temperature of the greywater is dependent on the surrounding and source temperatures. Usually, greywater is at a higher temperature than ambient conditions because it originates from a heated source i.e. hot water for bathing, laundry and hand washing (Gross et al., 2015).

This case study presents a successful combination of greywater recycling, using the MBBR system, and heat recovery, see Figure 5.6 at a passive residential building in Berlin, Germany. The system serves 41 flats housing 123 people and 4 commercial units, see Figure 5.5 and receives about 3000 l/day of low load greywater, the recycled greywater is used for toilet flushing. The recycled greywater (showers and baths) yields only 22 l/p/d which is not sufficient to meet the service water demand (27 l/p/d) for toilet flushing. In Figure 5.7, the black line represents the amount of greywater from showers and bathrooms and the green line represents the water demand for toilet flushing. Comparing the black and green lines, it is evident that greywater from the showers and bathrooms is not able to meet the water demand for flushing toilets and needs to be supplemented. This can be solved by including kitchen and laundry greywater to the existing greywater stream (Nolde et al., 2014).

Figure 5.5. Multi-storey passive house at Arnimplatz housing, a combined greywater recycling and recovery system. The system is located in the basement of the building occupying an area of approximately 9 m2. Photo extract: (Nolde et al., 2014). Published with permission from Erwin Nolde.

The heat energy is harvested by heat exchangers. Warm greywater entering the treatment system first passes through heat exchangers before undergoing biological treatment using the MBBR system. The MBBR greywater treatment system used at Arnimplatz (Figure 5.6) is similar to the MBBR treatment system used at the Roof Water Farm in Berlin and described in section 4.1 of the report. The heat recovered is used for preheating cold water before entering the building's heating system (Nolde et al., 2014). The Figure 5.6 shows the schematic of the greywater recycling using MBBR system and heat recovery system using heat exchangers.

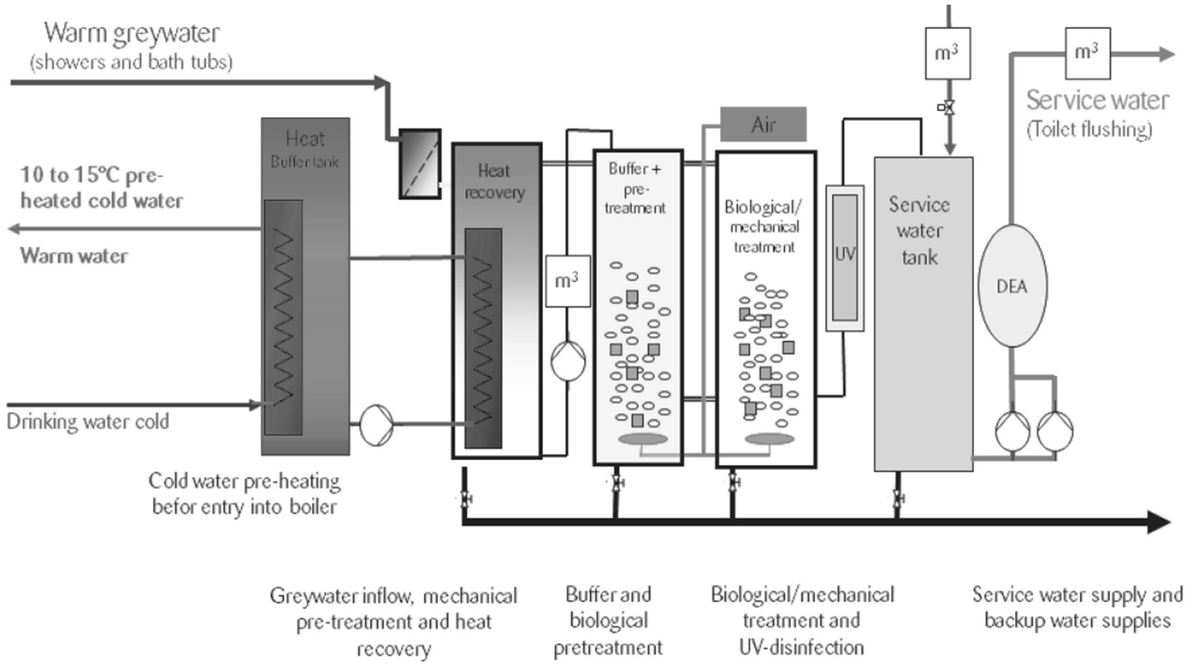

Figure 5.6. A schematic of the greywater treatment system including heat recovery for the passive residential building in Berlin, Germany (Nolde et al., 2014). Published with permission from Erwin Nolde.

From Figure 5.7, the monitoring results for the greywater recycling and heat recovery system at Arnimplatz, Berlin suggest that more than 40 kWh/d of thermal energy savings (the top-most solid black line on the graph) is often recovered from the system The amount of thermal energy savings depend on the amount of greywater generated and the freshwater demand. The total electric energy demand (line at the bottom-most of the graph) of the entire system (heat recovery, greywater treatment and service water distribution) is 4 kWh/d (Nolde et al., 2014).

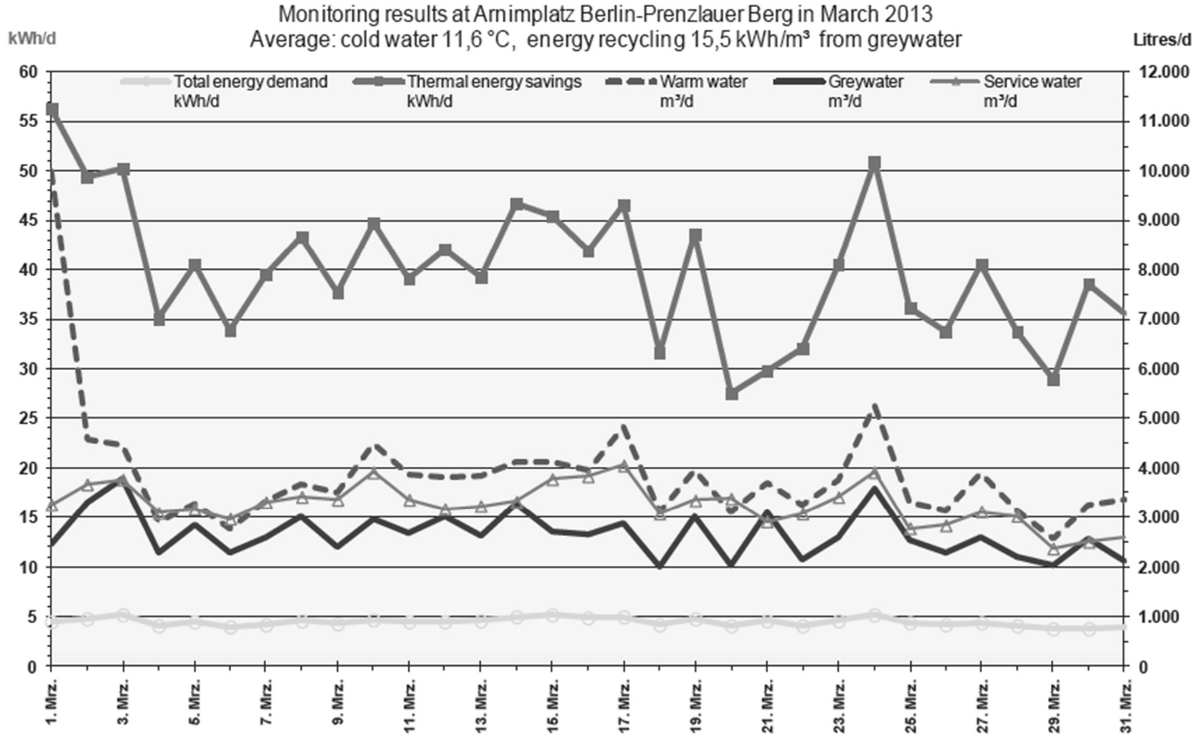

Figure 5.7. A figure showing monitoring results for March 2013 at the passive residential building at Arnimplatz in Berlin, Germany (Nolde, 2014). Published with permission from Erwin Nolde.

6 Results and Discussions

This chapter of the report aims to present and discuss the results obtained after incorporating the findings of the comprehensive literature review and site visit with the formulated selection criteria.

The initial literature review produced a number of hits for methods used in greywater treatment, *see* Table 5.1. Most of the GW treatment systems found in the literature did not meet the selection criteria formulated in section 3.1 of the report.

The selected treatment methods are presented and discussed in the subsequent sections of this chapter. Finally, the selected treatment systems are also evaluated against the evaluation criteria in section 3.2 of the report. The evaluation criteria assesses the performance of different selected greywater treatment systems.

6.1 Selection of relevant treatment systems

Not all the literature gathered was relevant to the thesis study. The literature was assessed and narrowed to be relevant to the Oceanhamnen area with help of the selection criteria, *see* Table 5.1. The selected greywater treatment methods are presented and discussed in this section of the report.

The selected greywater treatment methods include; RBC, MBBR, MBR, constructed wetland and a combination of aerobic biofilters and constructed wetlands. Some of the relevant case study applications of the selected greywater treatment systems are summarized in Table 6.1 to give the reader an idea of how relevant the selected treatment systems are to the Oceanhamnen area. A detailed description of each of the case studies for each treatment method is presented in section 5.1 of the report.

Table 6.1. A table summarizing the different selected greywater treatment methods. The table presents some of the case studies where the selected greywater treatment methods have been successfully used. The table shows the treatment method together with any additional treatment used alongside it, the location and the size e.g. number of people or buildings served by the treatment system.

Selected method		**Location**	**Start Year**	**Size (Persons)**	**Reference**
1. RBC	(a)	Technon campus, Israel			(Friedler et al., 2005)
	(b)	Berlin, Kreuzberg, Germany	1989	70	(Nolde, 2000)
2. MBBR	(a)	Arnimplatz, Berlin	2012	126	Nolde et al., 2016
	(b)	Roof Water Farm, Berlin	2006	250	Nolde et al., 2006
3. MBR	(a)	Technon campus, Israel			Friedler et.al., 2005
	(b)	SCST, Berlin		50	Lesjean & Gnirss, 2006
4. Constructed wetland		Kalmar, Sweden	1995-97	500	Günther, 2000
5. Aerobic biofilters and Constructed wetland	(a)	Klosterenga, Oslo	2000	100	Jenssen et al., 2010 Jenssen & Vråle, 2004
	(b)	Kaja, Norway	1997	48	Jenssen & Vråle, 2004 Jenssen et al., 2010)
	(c)	Torvetua, Norway	1998	140	Jenssen & Vråle, 2004 Jenssen et al., 2010

From Table 6.1, one important aspect to highlight is the size of the projects. Most of the case studies are pilot scale greywater treatment projects. This means that the treatment systems are designed for small scale operations and therefore serve a small number of people (100 - 250 persons). The Oceanhamnen area project is designed to serve a much larger size of approximately 2000 persons (about 8- 20 times the size of some of the selected cases in Table 6.1). The inception year of the projects is included (where possible), to show the longevity of the different projects. This proves that if any of the selected treatment methods is successfully implemented in the Oceanhamnen area then it could be reliable and operationally stable.

The location of the selected cases is relevant to location of the Oceanhamnen area in Helsingborg. Berlin, Oslo and Helsingborg are all cities in Europe. They experience the similar climatic conditions that are characterized by four seasons with winter, spring, summer and autumn. One could also argue that the consumption trends, lifestyles of people living in European countries are quite similar. One can thus assume that the composition of greywater in the three countries is relatively the same. Another important factor is that Sweden and Germany are members of the European Union (EU) and are therefore governed by the same regulations such as the EU bathing water quality regulation. Much as Norway is not part of the EU, the literature on the case studies (Kaja, Klosterenga and Torvetua) shows that effluent quality was compared to the EU bathing water quality regulations. Based on the above explanations, one can safely assume that any greywater treatment method that can successfully work in Norway and Germany, should yield similar results in Sweden. Lastly, a small footprint was required for all the selected cases because they are located in an urban environment just like the Oceanhamnen area in Helsingborg.

6.2 Evaluation of effluent quality

As mentioned earlier, one may assume that the consumption trends, lifestyles of people living in European countries are quite similar. Ultimately, this means that the composition of greywater in Germany and Norway is likely similar to composition in Sweden and consequently in Oceanhamnen area. The effluent concentrations of the different case studies (Table 6.1) are presented in Table 6.2 after treatment by the selected greywater treatment systems. It is important to highlight that the greywater influents are of varying qualities and volumes for the different case studies. Nonetheless, a comparison of the results in Table 6.2 gives the reader an idea of the effectiveness of each selected treatment system in reducing contaminants in the greywater.

From Table 6.2 it is evident that construction wetland systems attain significantly higher P removal compared to RBC, MBR and MBBR systems. A combination of aerobic biofilters and constructed wetland containing light weight expanded clay aggregate yield even higher P removal than a constructed wetland alone. The constructed wetland seems the best choice for P removal among the treatment methods. However, constructed wetland system is unsuitable for urban projects since urban environments require a small area footprint, *see* section 3.1.1 of the report. Higher phosphorus removal can be achieved by improving the other treatment systems e.g. using chemical precipitation in the MBBR system. Unlike the significant differences in P values in the effluent, N values in the effluent are almost similar for all the treatment methods. All the treatment systems i.e. RBC, MBR, MBBR, constructed wetland and aerobic biofilters and constructed wetlands attain significantly high *E.coli* removal. The *E.coli* concentrations in Table 6.2 are all lower than the recommended maximum value of 1000 colony forming units per 100 ml for inland waters of 'good' quality. All the treatment systems also attain significantly low turbidity of < 2 NTU.

Table 6.2. A table showing the effluent concentrations (as found in the relevant literature) after treatment using the RBC, MBR, MBBR, constructed wetlands, aerobic biofilters and constructed wetlands.

Selected treatment method	**No.**	**Location**	**TP**	**TN**	**BOD**	**Turbidity**	***E.coli***	**Reference**
Units			mg/l	mg/l	mg/l	NTU	cfu/100ml	
1. RBC		Technon campus	2	1	2.3	0.61	0.1	Friedler et al., 2005
2. MBR	(a)	SCST, Berlin	3.5	10				Lesjean & Gnirss, 2006
	(b)	Technon campus			1.1	0.2	0	Friedler et al., 2006
3. MBBR	(a)	Roof Water Farm, Berlin	2.42	4.8	1.6 [a] < 5[b]	< 1	2 - 3	Nolde et al., 2016[b] Saidi et al., 2017[a]
	(b)	Arnimplatz, Berlin			< 5	< 2	< 1000	Nolde et al., 2014
4.Constructed wetland		Kalmar, Sweden	0.22	1.6	0		43	Günther, 2000
5. Aerobic biofilters & constructed wetlands	(a)	Klosterenga, Oslo	0.03	2.5	5.0		0	Jenssen, 2005
	(b)	Kaja, Norway	0.07	2.5	6.9		$0 - 10^3$	Jenssen & Vråle, 2004
	(c)	Torvetua, Norway	0.21	2.2	5.5		< 1000	Jenssen & Vråle, 2004

6.3 Evaluation of discharge limits

Before greywater can be reused or discharged, sufficient treatment of greywater is needed to ensure that the effluent is of an acceptable quality and hence safe for reuse or discharge. There are a number of regulations which recommend the minimum requirements depending on the intended effluent reuse applications. An overview of some of the discharge regulations and possible ways used to achieve acceptable discharge limits are presented in section 2.2 of the report. In this section of the report, the selected greywater treatment methods are assessed based on a number of water regulations and local discharge limits to ascertain the effectiveness of the treatment regimes in ensuring a safe reuse or discharge. A further comparison with the discharge limits for the local Öresundsverket WWTP in Helsingborg is also carried out.

6.3.1 Evaluation against EU bathing water quality

The EU bathing water quality regulation provides guidelines for ensuring acceptable effluent quality for bathing waters in Europe. This regulation measures the quality of bathing waters in terms of the amount of colony-forming units of *E.coli* per 100 ml. The regulation categorizes the bathing water quality as either 'excellent', 'good', 'sufficient' or 'poor', *see* section 2.2.1 of the report.

There is always a risk for human body contact and ingestion of the GW effluent when reused; whether in water parks or toilet flushing. Based on this, only the EU bathing water quality regulation categories of 'excellent' and 'good' water quality are deemed acceptable for ensuring safety and good health of the population. Considering the location of the proposed water park in Oceanhamnen, it qualifies as either 'inland waters' or as 'coastal and transitional waters'. For a 'good' quality, the EU bathing water quality regulation recommends a maximum of 1000 colony forming units per 100 ml for inland waters and 500 colony forming units per 100 ml for coastal and transitional waters while for an 'excellent' quality, the EU bathing water quality regulation recommends a maximum of 500 colony forming units per 100 ml for inland waters and a maximum of 250 colony forming units per 100 ml for coastal and transitional waters, *see* Table 2.2.

Table 6.3. A table showing E.coli concentrations (cfu/100ml) in the effluent quality from the selected greywater treatment systems.

Selected treatment method	No.	Location	*E.coli* (cfu/100ml)
1. RBC		Technon campus	0.1
2. MBR	(a)	SCST, Berlin	
	(b)	Technon campus	0
3. MBBR	(a)	Roof Water Farm, Berlin	2 - 3
	(b)	Arnimplatz, Berlin	< 1000
4.Constructed wetland		Kalmar, Sweden	43
5. Aerobic biofilters & constructed wetlands	(a)	Klosterenga, Oslo	0
	(b)	Kaja, Norway	$0 - 10^3$
	(c)	Torvetua, Norway	< 1000

From the Table 6.3, the *E.coli* concentrations in the effluent water quality from all the selected treatment methods lie within the category of 'good' quality for inland waters that requires a maximum of 1000 colony forming units per 100 ml in order to meet the requirements of the EU water bathing quality regulation. This means that all the selected treatment systems can be successfully used for treating greywater for reuse in the water park at Oceanhamnen. The *E.coli* concentrations in the effluent from the RBC, MBBR system at the Roof water farm, constructed wetland at Kalmar University and the aerobic biofilter and construction wetland at Klosteranga are all below the most stringent category ('excellent' quality for coastal waters) of the EU bathing water quality regulation. The 'excellent' category recommends a maximum of 250 colony forming units per 100 ml.

6.3.2 Evaluation against Swedish drinking water quality (Livsmedelsverket).

As mentioned earlier, there is a risk that effluent in a water park may be consumed and ingested especially by children. For this reason, the effluent quality from the selected treatment systems is assessed against the Swedish drinking water quality requirements.

The effluent concentrations highlighted in 'bold' in Table 6.4 do not meet the Swedish drinking water quality requirements. The effluent turbidity (0.61 NTU) from the RBC treatment system falls short of the maximum requirement of 0.5 NTU stipulated by the Livsmedelsverket. A turbidity of

0.61 NTU seems like a good result and for that reason, it is important to note, that the Swedish drinking water quality requirements are by far more stringent than the other discharge limits discussed in this report. Considering Table 6.4, it is bit challenging to compare Total N measured in greywater effluent to the Swedish drinking water requirements since the N concentration in drinking water is measured in terms of Nitrate (NO_3) and Nitrite (NO_2) concentrations. Therefore, any conclusions based on comparisons between Total N and nitrates or nitrites may lead to uncertainties in the future. Some of the effluent results for E.coli concentrations and turbidity are given in the literature as ranges rather than exact values. This also makes it difficult draw a conclusion on whether a system meets the recommended values. This means that there is need for better measurements of Total N (NO_3 and NO_2), turbidity and *E.coli* before concluding that the effluent meets the drinking water limits. Based upon the uncertainty arising from comparisons of Total N with Nitrate (NO_3) and Nitrite (NO_2) measurements when using Swedish drinking water regulation, the EU bathing water quality standard was used as the main water regulation in this thesis report.

Table 6.4. A table showing a comparison between the maximum Swedish drinking water limits (Livsmedelsverket) and the effluent quality from the selected greywater treatment systems.

Selected treatment method	**No.**	**Total N**	**Turbidity**	***E.coli***
Units		mg/l	NTU	cfu/100 ml
Livsmedelsverket (2001)		50 (NO_3) 0.5 (NO_2)	0.5	100
1. RBC		1	**0.61**	0.1
2. MBR	(a)	10		
	(b)		0.2	0
3. MBBR	(a)	4.8	< 1	2 - 3
	(b)		< 2	< 1000
4.Constructed wetland		1.618		43
5. Aerobic biofilters & constructed wetlands	(a)	2.5		0
	(b)	2.5		0 - 10^3
	(c)	2.2		< 1000

6.3.3 Evaluation against Local (Öresundsverket) WWTP discharge limits

The proposed project is in close vicinity to the existing WWTP (Öresundsverket) in Helsingborg and could be an interesting comparison of the effluent quality once the proposed greywater system is in operation.

The effluent concentrations highlighted ‘bold’ in Table 6.5 do not meet the local discharge limits at Öresundsverket WWTP. The effluent P concentrations (mg/l) from RBC, MBR and MBBR treatment systems fall short of the 0.5 mg/l P discharge limit at the Öresundsverket. However, the constructed wetland and aerated biofilter treatment systems show significant reduction in the effluent P concentration up to 0.03 mg/l. Subsurface constructed wetlands contain plants which take up phosphorus contributing to P reduction as greywater passes through the constructed wetland. The biofilters are fitted with a Filtralite, a light-weight expanded clay aggregate possessing high phosphorus sorption capacity. For the greywater treatment system at Klosterenga in Oslo, aerated biofilters were used in combination with a constructed wetland, this could elucidate the achievement of high P reduction in the effluent. This further explains the higher P reduction achieved using the combined biofilter and constructed wetland. The BOD and N concentrations in the effluent for all the treatment methods fall below the Öresundsverket WWTP discharge limits of 10 mg/l. From Table 6.5, the aerobic biofilters & constructed wetland treatment systems have the highest BOD values in effluent ranging from 5.0 – 6.9 mg/l while the MBR systems have the highest N concentration in the effluent ranging from 4.8 – 10 mg/l. there is therefore need to improve phosphorus removal abilities for MBBR, RBC and MBR systems since constructed wetlands are deemed unsuitable for the Oceanhamnen project. Phosphorus removal maybe increased by use of chemical precipitation.

Table 6.5. A table showing a comparison between N, P and BOD concentrations in the effluent quality from the selected greywater treatment systems and the Öresundsverket, the local WWTP in Helsingborg.

Selected treatment method	**No.**	**Location**	**TP**	**TN**	**BOD**
Units			mg/l	mg/l	mg/l
Öresundsverket WWTP			0.5	10	10
1. RBC		Technon campus	**2**	1	2.3
2. MBR	(a)	SCST, Berlin	**3.5**	10	
	(b)	Technon campus			1.1
3. MBBR	(a)	Roof Water Farm, Berlin	**2.42**	4.8	1.6 (< 5)
	(b)	Arnimplatz, Berlin			< 5
4.Constructed wetland		Kalmar, Sweden	0.22	1.6	0
5. Aerobic biofilters & constructed wetlands	(a)	Klosterenga, Oslo	0.03	2.5	5.0
	(b)	Kaja, Norway	0.07	2.5	6.9
	(c)	Torvetua, Norway	0.21	2.2	5.5

6.4 Summary of the evaluation criteria

This section of the report aims to present and discuss the results obtained from the assessment of the selected treatment systems against the evaluation criteria, *see* sections 6.4.1 to 6.4.4 of the report. The summary of the results and discussions in this section of the report is presented in Table 6.6.

Table 6.6. A table showing a summary of how the different selected greywater treatment methods performed against the evaluation criteria as discussed in sections 6.4.1 to 6.4.4 of the report.

Evaluation Criteria	**RBC**	**MBBR**		**MBR**		**Constructed wetland**	**Biofilters & CW**		
		a	**b**	**a**	**b**		**a**	**b**	**c**
Footprint (area)	?	✓	✓	✓	✓	✗	✗	✗	✗
Size / Capacity	✓	✓	✓	✓	✓	✓	✓	✓	✓
Effluent water quality									
EU bathing water quality	✓	✓	✓	✓	✓	✓	✓	✓	✓
Swedish drinking water quality	✗	?	?	?	✓	✓	✓	?	?
Öresundsverket WWTP discharge limits	✗	✗	✓	✗	✓	✓	✓	✓	✓
Reliability									
• Full scale • Operation > 5 years	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ - means that the treatment method fulfils the description of the evaluation criteria in question.

✗ - means that the treatment methods registers a negative (does not meet the description of the selection criteria in question). For energy consumption, it means that the treatment system has a high energy consumption.

? - No information could be found in the literature.

6.4.1 Foot print

The MBBR system at the Roof Water Farm, Berlin and the biofilter and CW at Klosterenga, Oslo prove that the selected greywater treatment systems can be successfully used in urban areas. Urban areas are constrained by limited space available for setting up treatment systems or expanding the already existing ones. Therefore, greywater treatment systems for use in urban areas must have a low footprint. Low area footprint can be achieved by selecting treatment methods that can, for example, be successfully installed below the ground or in the basements of buildings. The MBBR for the passive residential building at Arnimplatz, Berlin is housed in the building's basement. The

MBBR system occupies an area of 9 m^2 which is equivalent to a 0.1 space index (0.1 m^2/person) for a size of 126 persons.

At Klosterenga, aerobic biofilters are housed in domes that are installed underground while the wetland used is a constructed wetland; both the constructed wetland and biofilters are occupy a small space in the apartment's compound. The constructed wetland occupies an area of 110 m^2 which is equivalent to a 1.1 space index (1.1 m^2/person) for a size of 100 persons. The combined biofilter and constructed wetland system has a space index of 1.5 m^2/person.

The MBBR system in Berlin is preferable to the Biofilter and constructed wetland treatment system in Oslo because of the low space requirement. The constructed wetland serving 100 persons at Klosterenga has a footprint of 1.1 m^2/person for 100 persons. This would mean that a constructed wetland at Oceanhamnen area serving 2 000 persons requires an area of 2200 m^2 while an MBBR system for 2 000 persons would require 200 m^2 and a combined biofilter and construction wetland treatment system would require an area of 3000 m^2. The MBBR system is therefore preferable to the constructed wetland systems for the Oceanhamnen area because of its low space requirement.

Table 6.7. Table showing the summary of the space index (foot print) of the greywater treatment systems at Arnimplatz, Berlin and Klosterenga, Oslo.

Location	Treatment system	Size (Capacity)	Space index (m^2/person)
Arnimplatz, Berlin	MBBR	126 persons	0.1
Klosterenga, Oslo	Constructed wetland (only)	100 persons	1.1
	Biofilters and CW	100 persons	1.5

6.4.2 Size (Capacity)

The greywater treatment systems encountered in the literature and site visits serve sizes of between 100 - 250 persons. Greywater recycling has for a long time been focused on decentralized treatment systems serving individual households of 2-10 persons. Therefore, pilot greywater treatment systems e.g. MBBR systems at Roof Water Farm and Arnimplatz in Berlin, the combined biofilter and constructed system at Klosterenga which serve 250, 126 and 100 persons respectively should not be considered small in size. The Oceanhamnen project in Helsingborg is expected to serve 2 000 persons which is about 10 times the size of the pilot projects discussed in this report. Nonetheless, the pilot projects have shown great advancements in greywater treatment technologies. Such pilot projects have treated greywater without operational problems and can therefore form basis for prediction of trends for much larger greywater treatment projects.

6.4.3 Effluent quality

Effluent quality was a vital evaluation criteria for assessing the selected greywater treatment systems. The evaluation of effluent quality was based on three water standards; the EU bathing water quality regulation, the Swedish drinking water quality requirements and the local discharge limits of the Öresundsverket WWTP and was discussed in section 6.3 of the report.

All the selected treatment methods (i.e. RBC, MBR, MBBR, constructed wetland and a combined biofilter and constructed wetland) meet the water quality recommendations stipulated in the EU bathing water quality. There was no sufficient data on exact effluent values for the different treatment methods to draw reliable conclusions based on Swedish drinking water and Öresundsverket WWTP discharge limits. Nonetheless, a rough estimation was made and presented in Table 6.6. One could argue that basing on the greywater reuse application for the Oceanhamnen area i.e. a water park, then EU bathing water quality requirements take precedence over the other water regulations. However, it is also important not to overlook the risk posed by the microbial pathogens and bacteria in effluent if a suitable greywater treatment is not chosen. The EU bathing water quality standard is used to draw conclusions on effluent quality in this thesis report. It is however envisaged that in the near future conclusive evaluation of effluent quality using both EU bathing water quality and drinking water quality regulations can be achieved. This would yield more reliable and accurate conclusions.

6.4.4 Reliability

The data obtained from literature review and site visits could only be assessed from the operational cycle of the treatment systems. All selected GW treatment systems except the MBBR system at Arnimplatz in Berlin have been in operation for at least 10 years, *see* Table 6.1. MBBR system at Arnimplatz has been in operation for 5 years (since the year 2012). Such treatment systems can be deemed reliable and hence recommendable for use at the Oceanhamnen since there is proof of their ability to serve reliably throughout, so far, most of its design life (design life is usually > 5 years). Not much literature is available on the operation and maintenance of the greywater systems. However, the literature on MBBR systems used at the Roof Water Farm and passive residential building (Arnimplatz) in Berlin suggested that no operational or maintenance problems have been encountered since project start in the 2006 and 2012 respectively. This was further confirmed during an oral interview with Professor Nolde during the site visit to the Roof Water Farm. The combined biofilter and constructed wetland system at Klosterenga, Oslo has also not posed any operational or maintenance problems since inception in the year 2000 according to the information obtained during an oral interview with Professor Jenssen during the site visit. Systems that require little operational maintenance may be considered reliable systems. Therefore, the MBBR, RBC, MBR and the combined biofilter and constructed wetland treatment systems are reliable.

If a greywater treatment system is only tried and tested on a laboratory scale but never tried out at full scale; one can never surely know if such a system is reliable and can meet the required purpose on a large scale even if the laboratory results obtained are good. Only greywater treatment systems that are tested on a full scale were chosen from the literature because they are deemed more reliable than treatment methods that were only tested on a laboratory scale. For example, the MBBR systems are fully operational on a large scale at Roof Water Farm and Arnimplatz in Berlin while the RBC, MBR and combined biofilter and constructed systems are operational on large scale at Techno campus, Israel, and Klosterenga, Oslo respectively. This reliability of the treatment systems provides an assurance that once such systems are used at the Oceanhamnen area in Helsingborg, there is a high likelihood for achieving a successful operation.

7 Conclusions and Recommendations

7.1 Conclusions

The aim of the thesis was to identify suitable methods for treatment of source separated greywater for discharge into an urban environment such as Oceanhamnen in Helsingborg.

By use of a selection criteria; a number of relevant treatment systems were found. The RBC, MBBR, MBR, constructed wetland and the combined aerobic biofilter & constructed wetland greywater treatment systems were identified as possible treatment systems. Further detailed assessment of these treatment systems against the evaluation criteria concluded the following;

- The constructed wetland and the combination of the biofilter and constructed wetland systems achieved the highest level of phosphorus (P) removal. The MBR and MBBR systems achieved much lower P removal compared to constructed wetland systems. The MBR performed better than the MBBR in P removal. The MBR and MBBR achieved low BOD concentration in the effluent compared to the aerobic biofilter and constructed wetland system. All treatment systems (RBC, MBBR, MBR, constructed wetland and the combined aerobic biofilter & constructed wetland) evaluated meet the maximum requirements for the EU bathing water quality regulation. The combined system of aerobic biofilter and constructed wetland achieved the lowest *E.coli* concentrations in the effluent followed by the MBR and MBBR treatment systems. All treatment methods yield closely similar nitrogen (N) removal, the RBC system achieved the lowest N concentration in the effluent followed by constructed wetland system, the combined aerobic biofilter and constructed wetland system, the MBBR system and lastly, the MBR system.
- The MBBR system has a much smaller space index compared with constructed wetlands and biofilters.

Constructed wetland system and the combined aerobic biofilters & constructed wetland system would be a suitable method, however, both systems have been eliminated because they require a very large foot print that is not available at Oceanhamnen. The RBC system has been eliminated because of insufficient information from which a reliable conclusion can be drawn.

Both the MBR and MBBR systems can be successfully used to treat greywater for reuse though they is need to improve P removal abilities of each system. This may be achieved using enhanced biological treatment or chemical precipitation. Basing upon this thesis study, the MBBR system is the preferred choice (to the MBR system) as suitable greywater treatment for urban discharge (a water park) in Oceanhamnen.

7.2 Recommendations

One of the challenges is that the proposed greywater reuse project is the first of its kind, designed to serve approximately 2000 persons. As mentioned in section 6.4.1, the reference projects with greywater treatment systems found in the literature are considerably smaller in size, serving between 100-250 persons. Therefore, more detailed studies of the different selected treatment methods are needed to ensure that treatment systems can still attain effective treatment and meet water quality requirements even at such a large size.

There is limited literature on greywater treatment for large scale reuse e.g. recreational water parks. Whereas toilet flushing, irrigation and groundwater recharge are good steps towards more sustainable greywater reuse; further research is needed if greywater is to be reused for recreational purposes e.g. water parks where the effluent quality possesses a significant health risk to the population. There is also a lack of good public perception and acceptability of the quality of treated greywater effluent since there are not many pilot projects available to foster public confidence.

Another likely challenge with greywater reuse in a water park is the challenge of the cold winters where there is a likelihood of freezing. This would require shutting the water supply system to the water park during cold winters. In such a case, another greywater reuse application may be required to counter such challenges. The cold seasons would also mean the treatment system would have to cope with irregular flows.

According to the Swedish drinking water regulation, Total N in drinking water is expressed in terms of Nitrate (NO_3) and Nitrite (NO_2) concentrations contrary to the different treatment methods encountered in the literature for this thesis study. The effluent concentrations for the treatment methods are given directly as Total N measurements. Any conclusions that are based upon comparisons between such Total N and nitrates or nitrites measurements may lead to uncertainties in the future. Treatment of greywater at Oceanhamnen to meet Swedish drinking water regulation is recommended, however to effectively implement the Swedish drinking water regulation, further studies and effluent nitrate and nitrite measurements are needed in order to facilitate more accurate comparisons.

8 References

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9 Appendices

Appendix A: Site visit photos: Roof Water Farm, Berlin

Above: A photo of Block 6 (only the all-white buildings to the right side of the brown building). The residential building is served by the MBBR treatment system. The constructed wetland (seen in the photo) is currently only used for stormwater treatment.

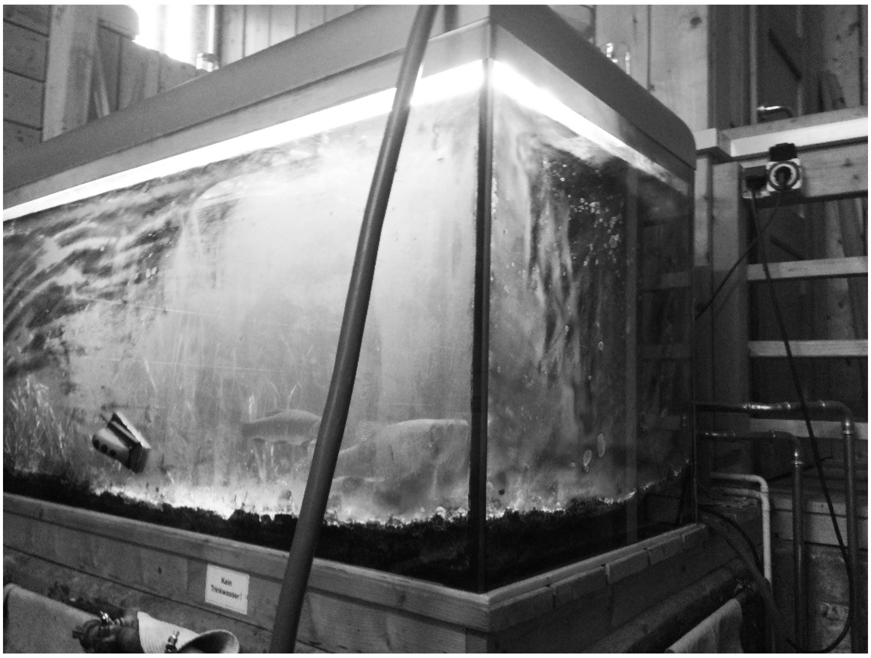
To the left:

A photo of the inlet to the MBBR system at the RWF, Berlin. From the inlet, the GW moves through a series of 10 treatment tanks (see photo below).

Above: A photo of the polyethylene tanks (10 tanks in series) that form part of MBBR treatment system at the RWF, Berlin.

Above: A photo of Professor Erwin Nolde of the RWF, Berlin sharing information with a group of visiting students (including me) during the site visit to the RWF, Berlin.

Above: An aerial-view photo showing the MBBR treatment system layout and operational controls at RWF, Berlin.



Above: A photo of an aquarium (with fish) inside at the RWF, Berlin proving that treated GW from MBBR system can supports aquatic life.

Appendix B: Site visit photos: Klosterenga, Oslo

The site visits to Berlin and Oslo took place during the winter season. Unlike Berlin that had the MBBR systems located indoors in a timber structure, the Klosterenga site is located outdoors. The entire site was covered with snow, hardly any useful photos could be taken. Nonetheless, below are some of the photos that were taken during the site visit to Klosterenga.

Above: A photo of the apartment building served by the GW treatment system (aerobic filters and a subsurface constructed wetland). The treatment system is located in the compound of the apartment building.

Above: The photo showing part of the compound where the treatment system is located. The aerobic bio filters are housed in domes that were buried below ground (under the compound). The concrete structure (in this photo) outlines the area where the domes are located.

Above: A photo showing the surface of the Constructed Wetland.

Appendix C: Site visit Questionnaire

1. What are the goals of the installation? What criteria was used to select the proper greywater treatment method, e.g. was the criteria based on space limitations, cost implications, discharge demands or similar?

2. What made you choose the particular treatment method/technology adopted at the facility? Were other treatment methods evaluated for suitability before this particular method was selected? If yes, what criteria was used to narrow down the scope of the different treatment methods that were evaluated? Could other methods have been successful, now that the system is operational?

3. What is the purpose of the treated effluent, is it strictly toilet flushing or irrigation or for a water park or are there any other reuse applications under consideration?

4. What discharge limits (nutrients, BOD, pathogens) are used? Are these limits following a particular regulation? Were there any exemptions from regulations received for this specific application? What are the effluent discharge values for nutrients (phosphorus, nitrogen, etc.), organic matter (BOD) and pathogens?

5. What size (e.g. number of people, households) is the project designed to serve? What is the amount of greywater generated and are there any storage to even out the daily variation in influent flow? After treatment, how is the greywater discharged? ***Specific to Oslo:*** *What happens to the water once it leaves the water park, is it discharged to the environment or re-circulated into the treatment system (at which stage does it rejoin the treatment system)*

6. What are the technical (operational) experiences / challenges encountered, now that the operation is in progress? How have you managed to deal with these challenges?

7. What management experiences / challenges (i.e. non-technical issues) have you encountered and how have you managed to solve them (e.g. any challenges with securing permits, juridical issues, economic issues or social acceptability)?

<u>Other relevant questions</u>

8. Are there any adjustments in the system to keep up with evolving lifestyles that come with increased micro pollutants e.g. to deal with increased use of home and body care products, pharmaceuticals, etc.

9. How do you deal with discharge to areas where there is human and animal interactions with the treated water? From a hygiene safety perspective, for example diseases that are spread through contact with water? **Specific to Klosterenga, Oslo:** *More microorganisms are likely to spread in aerosol e.g. when dealing with water parks!*

10. How is the stormwater managed on the sites? Is it separately treated/managed or is it jointly treated in the greywater system?

11. **Specific to RWF, Berlin:** Is there much published information on the greywater treatment project that is ongoing in Frankfurt.

12. Are there are any other similar greywater projects around the around that you think are worth looking into in order to get for more information?

Appendix D: Additional information on GW treatment systems, locations and applications

No.	Method	Location	Brief description
1.	Drawer Compacted Sand Filter (DCSF)	Jordan	● Modified sand filter design ● Sand filter is broken down into several layers approximately 10 cm high, ● Each placed in a movable drawer stacked vertically, with each drawer separated by 10 cm of space. Ref: https://doi.org/10.1016/j.ecoleng.2015.04.042
2.	Short retention treatment	University of Reading	● Only greywater from bathrooms(including washbasins), no kitchen waste etc ● 12 batches collected from selected student bathrooms ● 10 minute filtration cycles (greatest reduction TDS and EC between 10 - 12 minutes). No recommended time for optimum filtration. ● Filtration device used was an Intex Krystal Clear TM 604 swimming pool filter pump with integral Intex type ‘A’ filter cartridges (Intex, 7 2010) and filter pump was manufactured to treat up to 2000 l/hr (Intex, 2010).
3.	Sequencing Batch reactor (SBR)	Tunisia	● Student shower rooms (El Manzeh students house) ● Source separation, 200 occupants / students ● Goal: remove nutrients and more cost effective treatment ● Activated sludge, from a local municipal WWTP, was inoculated in the reactor for start-up ● SBR operated under alternating anoxic–aerobic conditions over 20 days to reach steady state before the start of experiments. ● SBR system worked two cycles per day. The one cycle (12 h) consists of 30 min influent feeding, 5 h anoxic, 5 h aerobic, 1 h sludge settling and 30 min effluent discharging. Ref: DOI: 10.1016/j.desal.2006.11.017

4.	Rotary Biological contactor (RBC)	Berlin Kassel Frankfurt (large scale)	Berlin: • GW treatment plant is found in a 15 m2 basement (Berlin–Kreuzberg, Manteuffelstraße 41) treating the greywater from showers, bathtubs and hand-washing basins 2. Built in 1989 for GW from 70 persons (started with 2 stage RBC but replaced with a 4 stage RBC in 1997) 3. Less energy demand Ref: https://doi.org/10.1016/S1462-0758(00)00023-6 Kassel: 4. Housing settlement with 65 persons Frankfurt/Main: 4-star hotel (Arabella-Sheraton) with 400 beds 5. 90 l/guest/d of greywater are produced 6. Toilet flushing was about 50 l/guest/ day Ref:http://wst.iwaponline.com.ludwig.lub.lu.se/content/ppiwawst/51/10/203.full.pdf
5.	Fluidized-bed reactor	Berlin	10 Two-stage fluidized-bed reactor (Berlin–Wedding, Bornemannstraße 4) 11 Built in 1995 for treating the GW from shower and bathtub of a two-person household (one-family household) 12 System has a total volume of 165 l (stage 1: 105 l; stage 2: 60 l) and placed above the toilet in the bathroom 13 Treatment was for toilet flushing Ref: https://doi.org/10.1016/S1462-0758(00)00023-6
6.	A triplicate soil layer infiltration–wetland–pond system for greywater purification	Sweden	- Encourage subsurface flow and interaction with plants and microorganisms - Repeated process to increase pathogen, BOD and nutrient removal - Before entering the pond system, the water passes through a section filled with lime–gravel to increase the surface for organic material reduction by aerobic bacteria and to buffer pH (shore zone purification process).

			- After the last pond, the water is let into a sand filter system and is collected in a well. Kalmar, Sweden • House is designed for 500 students, with a total water use of about 400 m3/ yr. • Very lightly polluted GW, (only hand- and dishwashing). • Plant area requirement is about 1200 m2, almost same as the roof area of the building Ref: https://doi.org/10.1016/S0925-8574(99)00040-3
7.	Membrane bioreactor technology (MBR)	Berlin, Jordan	Submerged MBR (Jordan) • No need for post filtration and disinfection • Consists of bioreactor and ultrafiltration (UF) membrane module Ref: https://doi.org/10.1016/j.memsci.2014.11.010
8.	Slow filters (Sand and Slate waste followed by Granular Activated Carbon)	Brazil	• System installed at Campus II of the Foundation Regional University of Blumenau (FURB) in the city of Blumenau, Santa Catarina, Brazil. No specified no. of persons Sand filter • Turbidity, apparent color, COD and BOD removal of 61, 54, 56, and 56% resp. Slate waste • Turbidity, apparent color, COD and BOD removal of 66, 61, 60, and 51% resp. Ref: https://doi.org/10.1016/j.jenvman.2016.03.035
9.	Sedimentation, Biological treatment (RBCs or a trickling filter or plant-covered, Vertical-flow soil filter) then to a clearing tank followed	General applicability	• Funnel-shaped sedimentation tanks with automated sludge-removing devices proved most effective • Clearing tank to remove the biomass. Ref: https://doi.org/10.1016/S1462-0758(00)00023-6

	by Disinfection by UV before it is stored in the service water tank. Distribution of service water is achieved with a booster pump.		
10.	Sedimentation, CW, Sand filter connected to an artificial pond	Sweden	Toarp (Eco-village) • 150 inhabitants consuming 200 l/p/d. GW facility designed for 40 m^3/d • 3 chamber sedimentation tank • Root zone facility i.e. Constructed wetland (reeds) • Sand filter (Vertical flow) • Artificial pond

Appendix E: Popular Science Summary

Discharging wastewater into an urban water park

Greywater – a very sustainable solution to the global water crisis! Uncertainty over water availability in 2020 is very real. Many (not only water professionals) have picked keen interest in water resources and its management to ensure sustainability of the resource for the future. Many parts of the world are already facing water shortages.

It is therefore imperative to find sustainable solutions to water shortages as soon as possible to avoid catastrophes that may likely arise with water shortages. Greywater reuse is one of the most promising sustainable solutions to water shortages. Greywater is wastewater generated from showers (personal bathing), laundry washing and kitchen sinks (dish washing). Greywater is generated on a daily basis; this means that there is always a constant supply of it. This makes greywater an area of interest due to sustainability reasons. Separation of greywater and blackwater at the source point (source separation) means that blackwater (toilet water i.e. the most contaminated part of the domestic wastewater) is excluded, enabling the reuse of greywater after treatment.

Sweden is endowed with vast water resources. Sweden continues to venture towards sustainability and greywater reuse. Currently, there is an ongoing construction of building units equipped with source separation that is geared towards greywater reuse (as a water park) in the City of Helsingborg. The project is a collaboration between the city of Helsingborg and Nordvästra Skånes Vatten och Avlopp AB (NSVA). Once completed, the housing project (located in Oceanhamnen, Helsingborg) will encompass residential and office buildings for approximately 2 000 persons. Greywater collected from these buildings will undergo treatment before reuse in a water park in the vicinity. The thesis project task was concerned with the greywater treatment and more specifically the sort of treatment systems that can be successfully adopted to achieve the reuse objective.

Detailed literature review using a formulated selection criteria and site visits of successful pilot greywater treatment systems in Berlin, Germany and Oslo, Norway was carried out. The results obtained were further assessed using a formulated evaluation criteria before selecting the most suitable selection system. One interesting aspect of this thesis study was to draw the correct scope for the study. For example, Sweden experiences cold winters as well as summers that are relatively hot, the scope was therefore designed in a way to ensure relevance. In this case, areas that experience cold winters and warm summers were chosen. The project is located in a city with limited space. Therefore treatment systems with small area footprint were crucial if this project is to be realized. Footprint requirements eliminated constructed wetlands as possible treatment systems for Oceanhamnen. The quality of the treated greywater (effluent) was also of major focus during the thesis study. The effluent quality was assessed against applicable regulations to Sweden such as the EU bathing water quality regulation and Swedish drinking water quality requirements. Since the reuse purpose is a water park, the EU bathing water quality regulation took precedence. However, it was good to also compare the effluent to the Swedish drinking water requirements since there is a slight risk of water consumption especially for the playing children. Upon this assessment, the Moving Bed Biofilm Reactor (MBBR) was concluded to be the best suited treatment system for Oceanhamnen that would allow safe discharge of greywater into a water park in the city.

The results and conclusions achieved in this thesis study are first and foremost hoped to foster a successful greywater reuse on a large scale (a water park) in the city of Helsingborg – the first of its kind! Also importantly, greywater reuse is sustainable and studies (such as this thesis) on greywater reuse are important for the future. Areas such as Cape Town in South Africa and other areas experiencing water scarcity across the world, should look to greywater reuse as both an immediate and even a more long term solution to water problems. Greywater reuse is the hope for the future of water security.