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The practical performance of decentralized waste water treatment technologies in Dutch urban areas

Master thesis

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Summary

Over the last few years, the approach of waste water management is shifting from the conventional centralized treatment system to a modern decentralized treatment system including the separation of domestic waste water streams. The treatment of separated domestic waste water streams on local scale is considered to be beneficial for the treatment efficiency, the mitigation of local water shortages and the recovery of valuable resources. The concept of the decentralized waste water system is increasingly taken into consideration in the Netherlands. The implementation of decentralized waste water systems on neighborhood scale is more frequently put on the agenda. In fact, the system design phase has already started in multiple Dutch cities.

Yet, the selection of the most suitable treatment technology for a decentralized waste water system is not a clear-cut decision. Firstly, this challenge is caused by the variation among the available technologies. Each treatment technology has a specific set of theoretical benefits and limitations (product specifications). Secondly, the performance of a technology in actual practice is dependent on contextual influences from the specific location of application. Thus, no 'one-size-fits-all' solutions exists for the selection of a decentralized waste water treatment technology.

In order to contribute to the selection of the most suitable treatment technologies for the implementation in Dutch urban areas, this study aimed to evaluate on how the product specifications will manifest in practice. Therefore, product specifications and the actual performance of the vertical subsurface flowing constructed wetland and the DESAH system were analyzed. The product specifications and the actual performance were analyzed on 11 distinctive aspects divided over the environmental, functional, economic and sociocultural dimension.

The results of this study show that for the vertical subsurface flowing constructed wetland and the DESAH system the actual performance of the assessed technologies partly comply with the product specifications. This report presents in detail whether the actual performance complies with the product specifications on each technology aspect. What theoretical benefits will manifest in practice, and what actual challenges should be taken into account during the design of a waste water system?

List of Abbreviations

Units and quantities

€	Euro
˚C	Degree Celsius
BOD	Biological oxygen demand
BOD_5	Biological oxygen demand after a 5-day period
cfu	Colony-forming unit
COD	Chemical oxygen demand
d	Day
dB	Decibel
h	Hour
HRT	Hydraulic retention time
kWh	Kilowatt-hour
l	Liter
m	Meter
mg	Milligram
mm	Millimeter
p.e.	Polluter equivalent
pfu	Plaque-forming unit
µg	Microgram

Chemicals

K, K^+	Potassium, Potassium ion
Mg^{2+}	Magnesium ion
N	Nitrogen
NH_4^+	Ammonium ion
NO_2^-	Nitrite ion
NO_3^-	Nitrate ion
P	Phosphorus
PO_4^{3-}	Phosphate ion
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids

Organizations

EVA	Ecologisch centrum voor Educatie, Voorlichting en Advies
Kiwa	Keuringsinstituut voor Waterleiding Artikelen
KWR	KWR Water Research Institute
RIVM	Rijksinstituut voor Volksgezondheid en Milieu
STOWA	Stichting Toegepast Onderzoek Waterbeheer
VROM	Volkshuisvesting Ruimtelijke Ordening en Milieubeheer

Other

AerAOB	Aerobic ammonium oxidizing bacteria
AnAOB	Anoxic ammonium oxidizing bacteria
E. coli	Escherichia coli
FOG	Fat, oil and grease
FWS-CW	Free water surface constructed wetland
HSSF-CW	Horizontal subsurface flowing constructed wetland
IBA	Individuele Behandeling van Afvalwater
NL	The Netherlands
O&M	Operation and maintenance
OLAND	Oxygen-limited Autotrophic Nitrification/Denitrification
RBC	Rotating biological contractor
UASB	Upflow anaerobic sludge blanket
VSSF-CW	Vertical subsurface flowing constructed wetland
WWTP	Waste water treatment plant

For the convenience of the reader of this report the term ‘DESAH system’ is used in order to refer to the UASB-OLAND-struvite-grey-water combination.

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1. Introduction

1.1 Developments in waste water treatment

The importance of waste water systems is acknowledged since the early civilization. Over the last 5,000 years, communal waste water systems have developed from open drainage systems through the streets to large-scale treatment of any type of waste water (Lofrano & Brown, 2010). The classical objective of waste water treatment is to facilitate the disposal of effluents without endangering human health or causing intolerable damage to the natural environmental (Sonune & Ghate, 2004). Although many years of development have past, the improvement of waste water treatment technologies and their management is still of global relevance. On the one hand, this relevance is motivated by the fact that many households are still not connected to any type of waste water treatment facility. These households are mainly located in developing countries or at remote areas (United Nations, 2015). On the other hand, the relevance is driven by the desire to find the most suitable way to deal with domestic waste water, also in areas that are already connected to a treatment facility.

Over the last decade calls have been made for a shift in the approach of dealing with domestic waste water. Instead of focusing solely on the large-scale centralized waste water treatment facilities, also a decentralized distribution of the facilities needs to be considered (Larsen et al., 2009; Rittmann, 2013; Water Europe & PNO, 2017). Since these calls, the advantages and opportunities of the decentralized approach have been highlighted. Often named benefits are the minimization of waste water transport volumes and distances, the contributions to the prevention of local water shortage and the establishment of a treatment system that is more adaptable to future changes (CWA, n.d.; Falkenmark & Xia, 2013; Rittmann, 2013).

In order to maximize the benefits from the decentralized waste water treatment, the different waste water streams from a household should be separated instead of mixed in one sewer. By separating the streams, the treatment can be performed independently. By doing so, the removal of pollutants can be more specifically targeted and the recovery of resources from the waste water can be performed efficiently (Joss, A.; Siegrist, H.; Ternes, 2008; Kujawa-Roeleveld, 2005; Larsen et al., 2004). Larsen & Gujer (2013) suggested that the inclusion of at-the-source separation is essential to maximize the benefits from decentralized waste water treatment.

Contrarily from the benefits and opportunities, multiple challenges are involved with a shift towards the decentralized approach. First, there is the undermining of the economies of scale that are involved with the conventional centralized approach (Tchobanoglous & Leverenz, 2013). By substituting a large waste water treatment plant (WWTP) for multiple small treatment facilities that are distributed over the connected area, higher financial costs, more operation and maintenance efforts, and an increased physical footprint are expected (Maurer, 2013; Tchobanoglous & Leverenz, 2013).

Moreover, challenges arise related to the urban integration of decentralized treatment facilities. Cities are densely populated areas, with a high cumulative waste water generation rate. While this leads to a high demand for waste water treatment capacity, cities commonly have little space to harbor waste water treatment facilities. Hence, the challenge of an increased physical footprint especially becomes problematic in urban areas. Furthermore, the public opinion on the adoption of a decentralized treatment system is much fiercer in urban areas than in rural areas. Compared to rural locations, the demands of urban communities are higher concerning potential changes in personal comfort, personal costs and environmental performances of the system (Larsen & Gujer, 2013).

1.2 Increasing interest in the Netherlands

Regarding the theoretical advantages and challenges that are discussed, it appears to be not straightforward whether the application of a decentralized system in urban areas is a suitable improvement. Nonetheless, the implementation of a decentralized waste water treatment system is increasingly taken into consideration in the Netherlands in recent years (Palsma & Swart, 2009). Currently, a shift towards decentralization is intended by multiple Dutch (semi-)governmental bodies that are responsible for the water management in densely populated neighborhoods. Amongst others, neighborhoods in Utrecht, Amersfoort, Nieuwegein, Boekel, Katwijk are designated for the implementation of this novel concept (*Beeldkwaliteitsplan Soesterhof*, 2014; *Waterplan – Ecodorp Boekel*, n.d.; Brightwork, n.d.; H2O, 2019, 2020; Nanninga et al., 2018; Vlot & Schilt, 2019; Waternet, n.d.). It is expected that the number of locations will grow further in the near future. This growth will partly be driven by the timing of an economic concern. Currently and in the near future, major components of the conventional domestic waste water system are becoming obsolete. Hence, investments are required for renovation or replacement. Therefore, the investments in decentralized options will be taken into consideration more often (Swart & Palsma, 2013).

1.3 Required knowledge for a beneficial system design

When such a consideration is evolved into the decision to implement a decentralized domestic waste water treatment system, the system design phase starts. The centerpiece of the system is the technology for the actual waste water purification. Hence, during the design phase the emphasis is in general given to the identification of the most suitable treatment technology. A range of treatment technologies is available for application in decentralized systems. Each of the technologies has its own specific set of theoretical qualities and limitations (Tilley et al., 2014). In this study, the technology-specific set of qualities and limitations is called the ‘product specifications’.

How the product specifications will manifest in actual operation of the technology is mainly determined by the local context of the implementation site. Hence, it depends on the location-specific circumstances whether a technology can be identified as the most suitable treatment technology (Capodaglio et al., 2017; Massoud et al., 2009; Singhirunnusorn, 2009; EPA, 2015). This dependence is seen as a primary problem during the implementation of decentralized waste water systems, since the geographical and sociocultural context are unique in every location (Guest et al., 2010).

1.4 Research aim and research question

In order to contribute to the selection of the most suitable treatment technology in specific contexts, this study aims to evaluate how the product specifications will manifest in the actual performance of decentralized domestic waste water technologies. Since multiple implementation projects are planned for cities in the Netherlands and even more are expected, this study will focus on the performance of the technologies that are applied in Dutch urban areas. In order to do so, the study addresses the following research question:

> Does the actual performance of decentralized domestic waste water treatment technologies comply with their product specifications when they are applied in urban areas in the Netherlands at neighborhood scale?

Here, the study will be guided by the following two sub-questions:

1. What are the product specifications of the decentralized domestic waste water treatment technologies that can be applied at neighborhood scale?

2. How do the decentralized domestic waste water treatment technologies actually perform in the Dutch urban areas?

2. Background information

2.1 Conventional waste water management in the Netherlands

The domestic waste water of more than 99% of all Dutch households is treated in WWTPs. The domestic waste water is generated by a variety of in-home water applications. These are the domestic waste water sources. In general, the waste water leaves the households via an in-home sewage network. Subsequently, the streams from all sources are combined and discharged as one mix to a neighborhood-level sewage pump. From there the domestic waste water mix is pumped and transported through pressure pipes towards one of the 350 Dutch waste water treatment plants (Hoogheemraadschap de Stichtse Rijnlanden, n.d.; Hoogheemraadschap van Delfland, n.d.). The sewer system in the Netherlands consists of approximately 100,000 kilometer of transport pipelines in the subsurface (Römgens & Kruizinga, 2013). In many locations, the fallen rain water is locally combined with the domestic waste water. However, since 1990 all newly build neighborhoods are provided with a separated rainwater discharge system. Mostly, the rainwater is directly discharged to local surface water bodies (STOWA & Rioned, n.d.-c).

After treatment in a WWTP, the purified domestic waste water is discharged to near surface water bodies as well. In 1970, the law on the contamination of surface water bodies (Wet verontreiniging oppervlaktewateren) issued and enforced the legal standards and monitoring plans for these effluent discharges. As a resulting effect, the treatment of communal waste water greatly improved in order to meet the water quality standards for disposal (Government.nl, n.d.). The legal water quality standards for WWTP effluent disposal are presented in Table 2-I.

Such quality standards also apply for small-scale treatment systems for domestic waste water. These standards were provided for the cases where polluters are not connected to the centralized waste water system. For a treatment system that treats the waste water of more than 10 polluter equivalent (p.e.), the quality standards of the IBA class IIIb apply (CIW, 1999). These legal effluent quality standards for the small-scale treatment systems are presented in Table 2-I.

In the Netherlands, two authorities are responsible for the performance of the conventional domestic waste water system. The government of a municipality (further called municipality) is responsible for the waste water transport between the households and the WWTP. The municipality manages the operation and maintenance of sewage components, such as the pipelines, wells and pumps. In order to do so, each household pays a financial tax to the municipality (sewage charges; in Dutch: rioolheffing) (Rioned, n.d.-b). The other involved authority is the local water board (in Dutch: Waterschap). Conventionally, the water board is responsible for the centralized waste water treatment in the WWTP and for the water quality in local water bodies (Rioned, n.d.-a). In order to fulfill these tasks, each household pays a financial tax to the water board (treatment charges; in Dutch: zuiveringsheffing) (Rijksoverheid, n.d.-a).

Furthermore, Dutch house owners bear the responsibility for the sewage components within the legal borders of the household property (Ons water, n.d.). Also for rental houses the maintenance of these components are under the responsibility of the property owner (Rijksoverheid, n.d.-b).

Table 2-I. Dutch legal quality standards for large-sized WWTPs, small-sized WWTPs and small-scale treatment system. All amounts are in mg l^{-1}.

Parameter	WWTP for 20.000-100.000 p.e. (InfoMil, n.d.)	WWTP for 2.000-20.000 p.e. (InfoMil, n.d.)	IBA class IIIb: Small treatment system for >10 p.e. (CIW, 1999)
BOD_5	20	20	20
COD	125	125	100
NH_4^+	-	-	2
TN	10	15	30
TP	1	2	3
TSS	30	30	30

2.2 Decentralized waste water treatment

2.2.1 Domestic waste water

As mentioned in the introduction, the at-the-source separation of domestic waste water streams plays an important role to the success of decentralized waste water systems. The separation makes it possible to treat the specific streams differently. The treatment of a separated stream can be optimized based on the characteristics of the specific waste water. As a result, the purification can be performed more efficiently and the recovery of resources (i.e. water, nutrients and energy) becomes more feasible. Furthermore, source separation of domestic waste water provides the option for a hybrid waste water system, where some streams are locally treated and some streams are treated in a central WWTP (Larsen et al., 2009).

In the literature related to the decentralization of domestic waste water, a distinction is made between 'black' and 'grey' waste water streams. In general, grey waste water is defined as all the domestic waste water that does not come in contact with fecal contaminants. It is assumed that only waste water generated in toilets and bidets is highly contaminated by fecal matter. Therefore this referred to as black waste water. Evidently, toilets and bidets are considered as black water sources. The sources of grey water are the bathtubs, showers, wash basins, kitchen sinks, dishwashers and washing machines (Kujawa-Roeleveld, 2005).

Precise numbers of the generation rates per source are hardly available, especially for the current Dutch situation. However, the potable water consumption rates per household activity are available for the average Dutch household in 2016. These consumption rates are shown in Table 2-II. Typically, the Dutch use potable water for all household activities that require water. Therefore, it is assumed in this study that the rates of potable water consumption is identical to the waste water generation rate for that activity or at that location in the house. One should realize that it is likely that these rates are probably not identical in actual practice. For example, people may drain cleaning water through the toilet, drain liquid food products through the kitchen sink and toilet flushing water is supplemented with feces and urine. However, the potential displacement of household water is not taken into account when quantitative waste water generation is analyzed.

Table 2-II. Average daily water consumption per household activity or source for the Netherlands in 2016. Adapted from Geudens & Grootveld (2017).

Source or activity	Water consumption ($l\ capita^{-1}\ d^{-1}$)	Share of total consumption (%)
Toilet	34.6	29
Bad tub	1.9	2
Shower	49.2	41
Wash basin	5.2	4
Laundry	15.4	16
Dishwashing	6	5
Food preparation	1.2	1
Tap water drinking	1.3	1
Undefined	4.5	4
Total	**119.2**	

Due to the different applications of the waste water generated at the various sources, the water quality of the black and grey waste water streams differ a lot. The black water stream exists of fecal matter, urine and flushing water. This stream is characterized by its high loads of organic matter, nutrients, microbial pathogens and pharmaceutical remainders. Since the volumes of fecal matter and urine are relatively small, the concentration is mainly determined by the amount of toilet flushing water. Nevertheless, the concentrations of these contaminants are high compared to grey water streams (STOWA, 2014). The combined grey water stream is characterized by its relatively low concentration of organic nutrients (compared to black water). The presence of inorganic nutrients originate from detergents and cleaning agents. Waste water from the kitchen may add high concentrations of food residues; fat, oil and grease (FOG); and thermo-tolerant coliforms to the combined grey water stream. Waste water generated in the bathroom generally contains high loads of personal care products, hairs and thermo-tolerant coliforms. Also, the grey water stream is characterized by its relatively high temperature, mainly caused by the warm water use in the shower and bath tubs. Further, applications in kitchen and laundry machine also contribute to the higher temperature (Gharehdaghy Mianjy, 2016; Kujawa-Roeleveld, 2005; Nanninga, 2011).

2.2.2 Decentralized waste water treatment technologies

Since 2017, the Dutch knowledge institutes Stichting Toegepast Onderzoek Waterbeheer (STOWA) and Stichting Rioned publish data and information about the implementation of decentralized waste water treatment technologies. They made a selection of treatment technologies for domestic waste water that are recommended for application in Dutch urban areas on neighborhood scale[a]. Within this selection, the technologies that are applicable for the treatment of both separated domestic waste water streams are the vertical subsurface flowing constructed wetland (VSSF-CW); the horizontal subsurface flowing constructed wetland (HSSF-CW); the free water surface constructed wetlands (FWS-CW); the willow field filter; the crop field filter; the compact system; and the combination of UASB reactor, OLAND RBC, struvite reactor and grey water treatment modules. These technologies are divided in two categories: nature based and high-tech (see Table 2-III).

In general, the nature based treatment technologies require more space than the more high-tech options. Of the nature based technologies, the vertical subsurface flowing constructed wetland (VSSF-CW) requires the least surface area. Therefore, this type of constructed wetland technology is, among the nature based options, most suitable for application in situations with little space left (e.g. densely populated areas). Furthermore, the willow filter and crop fields are hardly applied in the Netherlands. Very little information about the experiences with these nature based technologies is available (STOWA & Rioned, n.d.-g).

Besides waste water purification, the UASB-OLAND-struvite-grey-water combination targets the recovery of resources from the separated streams. The combination aims to contribute to various advantages of decentralized waste water treatment. The compact system does not appear to have more contributions to sustainability than a conventional WWTP (STOWA & Rioned, n.d.-a). Moreover, the compact system technology is generally applied as a temporal solution, for example in refugee camps or situations with an overloaded WWTP (STOWA & Rioned, n.d.-b).

Table 2-III. Decentralized domestic waste water technology options for Dutch urban areas according to STOWA & Rioned (n.d.-d).

Technology	Category
Free water surface constructed wetland (FWS-CW)	Nature based
Horizontal subsurface flowing constructed wetland (HSSF-CW)	Nature based
Vertical subsurface flowing constructed wetland (VSSF-CW)	Nature based
Willow filter	Nature based
Crop field filter	Nature based
Compact system	High-tech
UASB-OLAND-struvite-grey-water combination	High-tech

[a] This selection is published on: https://www.saniwijzer.nl/oplossingen/stedelijk-gebied/woonwijken

3. Methods

3.1 Research approach

The research was performed during a research internship at KWR Water Cycle Research Institute (KWR) located in Nieuwegein (the Netherlands). The research period for this master thesis started on the 24th of February 2020 and ended on the 21st of September 2020.

For the sake of time and profoundness of the study, two relevant technologies were selected for the analysis: the vertical subsurface flowing constructed wetland and the UASB-OLAND-struvite-grey-water combination. These two technologies for decentralized waste water treatment were selected because they are recommended for the application in urban areas on neighborhood scale (see subsection 2.2.2). Furthermore, multiple decisive authorities are currently considering the implementation of at least one of these two technologies in Dutch neighborhoods[b]. The UASB-OLAND-struvite-grey-water combination is developed by the company DESAH BV. Hence, the combination is referred to as the 'DESAH system' further in this report.

A qualitative research was conducted, primarily performed as a desk study. In order to provide a reference object for the study, the two technologies are delineated first. Therefore, the general design, technical functioning and available improvements of the technologies are studied at first. In order to answer the first sub-question, the product specifications of the two selected decentralized waste water treatment technologies were analyzed. The product specifications consist of statements and hypotheses from stakeholders with interest (e.g. technology sellers). Also, the product specifications are based on literature and expert statements that relate to the competences, benefits and limitations of the technologies in general or in another context (i.e. not in the Netherlands, not in urban areas, not on neighborhood scale, or not for domestic waste water treatment). Additionally, the actual performances of technologies in Dutch urban areas were evaluated to answer the second sub-question. The actual performances of the technologies resulted from the data that originated from monitoring and evaluation reports of the selected practical cases, the experiences of the end-users and the case-related information from the stakeholders with interest. By comparing the actual performances with the product specifications of both technologies, the main research question was addressed.

3.2 Assessment framework

In this study, the 11 assessment aspects of Balkema (2003) were used for the analysis of the product specifications and the actual performances of the decentralized waste water technologies. Balkema (2003) grouped the aspects in four dimensions of the decentralized waste water treatment technology: environmental,

[b] At least one of the two technologies is currently considered for neighborhoods in Amsterdam, Utrecht, Nieuwegein and Boekel.

functional, economic and sociocultural. The use of the assessment aspects is described below. Table 3-I summarizes the assessment framework.

Environmental dimension
The treatment efficiency, the effects on the local water balance, the nutrient recovery, the energy balance and the spatial requirements are the used assessment aspects in the environmental dimension of decentralized waste water treatment technologies.

In order to assess these aspects, the water treatment efficiency of the technology was analyzed by determining the contamination removal performance and the contaminant concentration in the effluent. Subsequently, the opportunities and performances of recovery, reuse local discharge of the effluent and the potable water savings were studied. Next, the opportunities of nutrient recovery from the treatment systems were analyzed. Additionally, the effects on the energy balance was determined by the energy requirements of the technology during operation and by the energy recovery during the water treatment. Furthermore, the spatial requirement of a technology was included as an assessment aspect. The required surface area and the change in qualities of the demanded space with respect to the urban context cover the performance of this aspect. The required quantity of space was expressed in covered surface area by the technology (in m^2) per polluter equivalent (p.e.). In general, 1 p.e. equals one end-user. The average Dutch household exists of 2.2 persons (CBS, 2019). Hence, if data about the amount of connected end-users is expressed in terms of ‘households’, it was assumed that this encompasses 2.2 p.e.

Functional dimension
In the functional dimension, the assessment aspects relate to the technical persistence in proper functionality. The first assessment aspect is called ‘the durability and reliability’. The durability was expressed in the average (expected) longevity of the system in years. The reliability was determined by the frequency and complexity of system errors that resulted in interruption of the functionality.

Additionally, the requirements of the technology to function properly were included. This was indicated by the time, effort, skill-level and materials that are needed for operation and maintenance (O&M) activities.

Economic dimension
The assessment aspects of the decentralized treatment technologies that were included in the economic dimension are the financial costs of investment and the operational costs. To assess the investment costs, the required costs for construction and project realization were included. The operational costs included the costs for maintenance, operation and resource input. Since this study focused on the Dutch practice, the costs were expressed in euros (€).

Sociocultural dimension
The performance of a technology in the sociocultural dimension is hard to quantify. Consequently, it is addressed less often in scientific analyses. However, the performance in this dimension is still proven to be important for a successful and

sustainable implementation of waste water technologies (Nayono, 2014). In this study, the sociocultural dimension of the decentralized treatment technology was covered by two assessment aspects. The first assessed aspects was the community involvement. This was indicated by the possibilities for end-users to participate in different stages of the implementation and operation process. Whether there are possibilities was determined by the required technology expertise and locally existing skills and understanding.

The second assessed aspect in the sociocultural dimension was the acceptance by the end-user. The acceptance was indicated by both positive and negative experiences and perspective of the end-user relate to the treatment system.

Table 3-I. Summary of aspects that are used to assess the product specifications and actual performance of decentralized waste water treatment technologies. The set of aspects is based on Balkema (2003).

Dimension	Assessment aspect	Expressing terms	Quantitative / qualitative
Environmental	Water treatment efficiency	Contaminant removal; effluent quality	Both
	Local water balance	Effluent reuse, recovery and discharge potentials; potable water savings	Both
	Nutrient recovery	Nutrient recovery potential and reapplication	Both
	Energy balance	Required energy input; energy recovery potential	Both
	Spatial requirements	m^2 per p.e.; change in spatial quality	Both
Functional	Durability & Reliability	Longevity in years; Technical errors	Both
	Operation & maintenance	Required time, effort, skill and materials	Qualitative
Economic	Investment costs	Costs in Euro (€) per p.e.	Quantitative
	Operational costs	Costs in Euro (€) per p.e.	Quantitative
Sociocultural	Community involvement	Required and existing expertise; process stages of involvement	Qualitative
	Acceptance	Positive and negative experiences and perspectives by the end-users	Qualitative

3.3 Criteria for the determination of compliance

In order to address the main research question, the results for the product specifications and the actual performance were compared. For each of the technology aspects in the assessment framework the compliance between the actual performances and the related product specifications was determined. Whether the actual performance complies with the product specifications was indicated by the symbols ‘Y’, ‘N+’, ‘N–’ and ‘n.c.’. The ‘Y’ confirms the compliance. The ‘N’ refers to disagreement between the actual performance and product specifications. The suffix ‘+’ indicates that the actual performance exceeds the theoretical benefits or lacks the theoretical limitations. The suffix ‘–’ indicates that the actual performance does not live up to the theoretical benefits and/or the actual performance exceeds the theoretical limitations. Lastly, the ‘n.c.’ indicates that too limited results were found for the product specifications or the actual performance on that aspects, and no credible conclusion could be drawn for the compliance.

Technical configurations of the two technologies that are not applied in the practical cases were not taken into account for the determination of the compliance.

3.4 Data collection

3.4.1 Collection methods

For each of the technologies, a literature study was conducted to collect the data for the analysis. The majority of the literature was retrieved online using several scientific search engines (i.e. Elsevier's Mendeley, Google Scholar, Microsoft Academic and Scopus). Also publication libraries of Dutch water industry-related knowledge institutes (i.e. Deltares, KWR , RIVM and STOWA) were consulted. Additionally, information was collected from webpages of VSSF-CW and DESAH system implementation projects, technology sellers/installers and domestic waste water related governments (water boards and municipalities).

In addition to the literature study, data and information were gathered through communication with technology experts. The communication consisted of semi-structured open-ended interviews and unstructured conversations. The interviewees were Dion van Oirschot (Rietland bvba – General Director), Martien Coopmans (VSSF-CW user), Ad van Ruijven (VSSF-CW user and daily operator) and Sybrand Metz (DESAH – Technical Director). The structure of the interviews (Appendix 1) was based on the technology aspects from the assessment framework, which is explained in section 3.2. The way of interviewing was done so that the interviewee could provide as much relevant information as possible, including information that might conflict their own interests. After the interviews, the collected data and information were arranged by the technology aspects for further analysis. The semi-structured interviews and the unstructured conversations with experts took place at the KWR and online (Microsoft Teams).

3.4.2 Practical cases

Multiple cases of technology implementation are reviewed in order to find detailed information about the actual performance of the treatment technologies in Dutch urban areas. The selection of the cases was based on the scope of the research question. So, the selected cases have implemented a technology (VSSF-CW or DESAH system) that treats domestic waste water in Dutch urban area at neighborhood scale. Since this research is mainly conducted as a desk study, an additional criterion was that there must be data available on the performance. Four practical cases were selected meeting these criteria, three VSSF-CW cases and one DESAH system case. The four cases are briefly described below and summarized in Table 3-II.

Polderdrift, Arnhem (VSSF-CW)

In 1991, Housing Society Gelderland organized an open competition for ideas concerning the design of a new eco-friendly and resource efficient neighborhood in Arnhem. The tenants would become the residents. From the proposed ideas a neighborhood of 40 households was developed: Polderdrift (see Figure 3.1 and Appendix 5). Polderdrift is located in the southern part of Arnhem. The residents rent the houses in Polderdrift. Currently, the neighborhood is maintained and rented out by Portaal (housing corporation).

The main objective of the design was to reduce the potable water consumption in the households. Hence, a semi-circular and local water system was established based on the separation of rainwater, grey water and black water. The rainwater of the roofs is collected and used to meet the demand of the washing machines. The residents are able to choose between rainwater and potable water supply to the washing machine in their own household. The greywater from the kitchens, bathrooms and washing machines is locally treated by a VSSF-CW system. This VSSF-CW system was constructed in 1997. After treatment, the treated effluent is used to supply the toilets in the households. The black water is discharged directly to the conventional sewer system and treated in the communal WWTP (Coopmans & Van Ruijven, 2020; Nanninga, 2011; Van Betuw, 2005).

EVA-Lanxmeer, Culemborg (VSSF-CW)

During the 1990s, the neighborhood EVA-Lanxmeer was realized according to the principles of the EVA (Ecological Centre for Education, Information and Advice) concept. The objective of this concept is to integrate sustainable resource management with an eco-friendly, urban and social lifestyle. The neighborhood is located in the south-west of the city of Culemborg. Currently, more than 300 houses, a large secondary school and five office buildings have been built in EVA-Lanxmeer. Since November 2003, there are three parallel VSSF-CW systems that treat the domestic grey water (Terra Bella, n.d.) (see Figure 3.2). Only the smallest system (located in the north-west) is currently functioning at full capacity. Because not all planned buildings are completed yet, the larger systems operate at approximately 50% of their capacity (Nanninga, 2011). After the treatment the water is discharged to the surface water body (Terra Bella, n.d.). Furthermore, EVA-Lanxmeer is located in a water extraction area of the drinking water company Vitens (Terra Bella, n.d.).

Drielanden, Groningen (VSSF-CW)

The aim of the Vereniging Ecologisch Wonen Groningen (Association Ecological Living Groningen) was to create a neighborhood with constructions and human living activities with a low environmental impact. Therefore, the urban water and energy cycles were designed to be more efficient compared to the typical Dutch neighborhood at that time. In 1995, the first houses were built in the Drielanden neighborhood in the north-eastern part of the city of Groningen. Since 1996, the neighborhood is provided with two FWS-CW systems for the treatment of the domestic waste water (Nanninga, 2011). However, in 2012 a VSSF-CW system was added. Since then, the waste water flows through the VSSF-CW first. Subsequently, the effluent is treated in the FWS-CWs. Afterwards the water is discharged to a nearby surface water body. In principle, only the grey water is treated by the constructed wetlands, and no pre-treatment of the grey water is performed. However, an increasing portion of the black water have been added for experimental purposes between September 2014 and January 2015. The added black water is treated in a septic tank first. Currently, 166 households are connected to the decentralized waste water treatment system (Gemeente Groningen, 2016) (see Figure 3.3).

Figure 3.1. Aerial view of the Polderdrift neighborhood (within red lines) and the VSSF-CW filter bed (within blue lines). Image adapted from Google (2017).

Figure 3.2. Aerial view of the EVA-Lanxmeer neighborhood (within red lines) and the three VSSF-CW systems (within blue lines) Image adapted from Google (2019a).

Figure 3.3. Aerial view of the Drielanden neighborhood (within red lines) and the VSSF-CW filter bed (within blue lines). Image adapted from Google (2018).

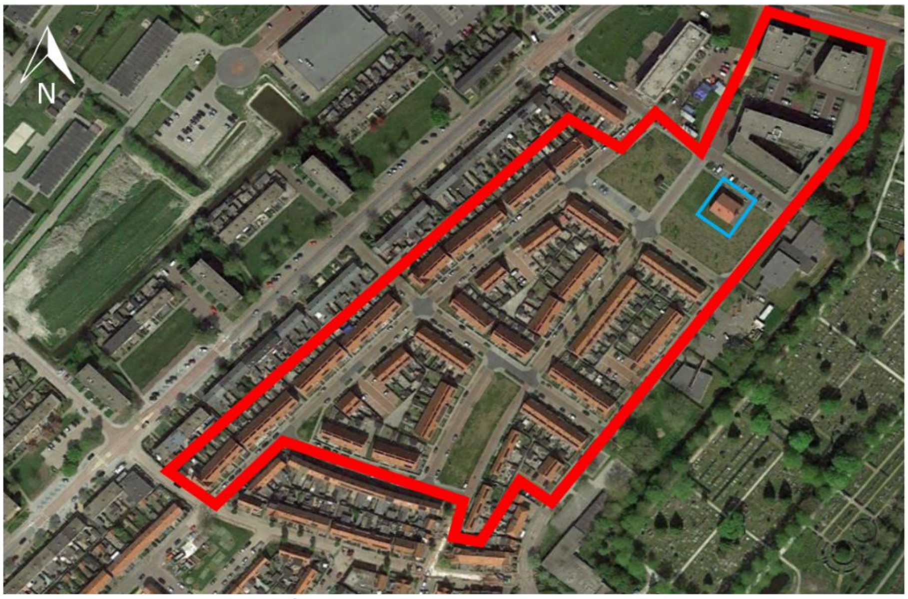

Figure 3.4. Aerial view of the Noorderhoek neighborhood (within red lines) and the DESAH system facility building (within blue lines). Image adapted from Google (2019b).

Noorderhoek, Sneek (DESAH system)

In 2008, home renovations started in the Noorderhoek, a neighborhood just north of the city center of Sneek. First a nursing home was built, and later family homes were renovated. The objective is to finish 232 households by the end of 2020. By then, all households are connected to a DESAH system, which treats the black water and grey waste water separately. Besides, small-sized kitchen waste is collected separately and treated together with the black water (Schets et al., 2017).

Next to the treatment of the waste water and small-sized kitchen waste, the objectives of the DESAH system in Noorderhoek is to recover energy and nutrients on local scale. In the center of the neighborhood a facility building (NUTS-gebouw) is built for the waste water treatment system and the resource recovery (De Wit et al., 2018) (see Figure 3.4).

The overall project is called 'Waterschoon'. The participating parties in the project are Housing association Elkien (formerly De Wieren), DESAH BV, the local water board (Wetterskip Fryslân), the municipality (Súdwest-Fryslân) and knowledge organization STOWA (De Graaf and Van Hell, 2014).

Table 3-II. Overview of the practical cases.

Treatment technology	Year of construction	Neighborhood (City)	Connected households	Waste water sources
VSSF-CW	1997	Polderdrift (Arnhem)	40	Kitchen sink, shower, washing bowls and washing machine (optionally rainwater supplied)
VSSF-CW	2003	EVA-Lanxmeer (Culemborg)	> 300 5 offices 1 school	Kitchen sink, shower, washing bowls and washing machine
VSSF-CW	2012	Drielanden (Groningen)	166	Kitchen sink, shower, washing bowls and portions of toilet (experimental)
DESAH	2008	Noorderhoek (Sneek)	232	All domestic waste water sources and small-sized kitchen waste

4. Vertical subsurface flow constructed wetlands

4.1 Description of the technology

4.1.1 General system set-up

The traditional vertical subsurface flow constructed wetland (VSSF-CW) systems consist of a primary and a secondary treatment stage. Optionally, tertiary treatment processes may be added dependent on the desired discharge or water reuse purpose (VROM & Kiwa, 1998). Figure 4.1 schematically presents the sectional view of a VSSF-CW systems. In the primary treatment stage, the domestic waste water is collected and stored in a septic tank (1). Inside the septic tank, floating particles are trapped by the upper barrier panels and sediment is trapped by the lower barrier panels (Global Wetland Technology, n.d.; Hoorn, 2017; Roest, 2015; Wetlantec BV, n.d.). Besides, biological activity occurs in the septic tank resulting in the reduction of biological oxygen demand (BOD) and the production of sludge. Black waste water requires a minimum retention time of four days in the septic tank. If only grey water is treated in the system, the septic can be omitted.

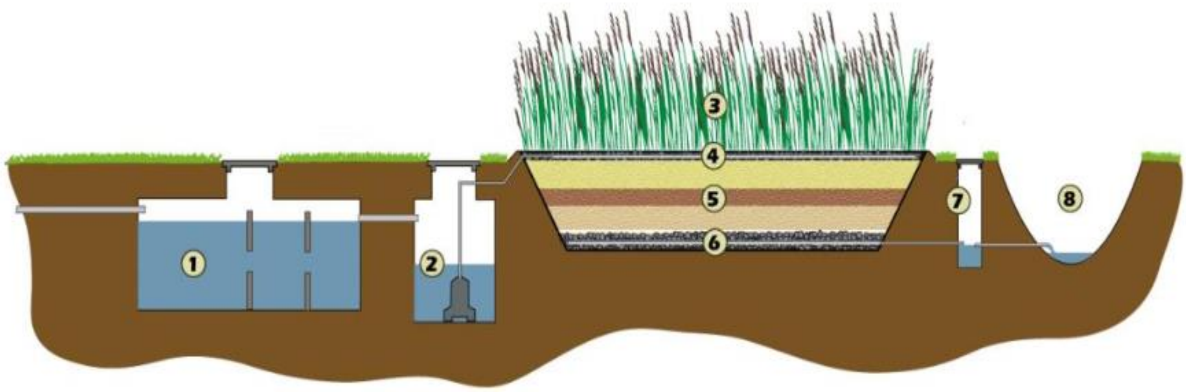

Figure 4.1. Schematic view of a VSSF-CW system. Illustration reprinted from Wetlantec BV (n.d.).

Although it is not shown in Figure 4.1, the primary treatment stage is completed by a fat, oil and grease (FOG) trap after the septic tank treatment (Spoelstra & Truijen, 2010; VROM & Kiwa, 1998).

After the waste water leaves the septic tank and FOG trap, the water enters a pumping well (2). Several times a day, the water is pumped and distributed over the surface of the VSSF-CW filter bed (4). From there, the water infiltrates into the soil bed. In the top layer of the soil bed (between 4 and 5), the rooting zone of helophyte type plants is located. Helophytes (3) are wetland species that have the ability to transfer oxygen (O_2) from the atmosphere into the rhizosphere (i.e. the soil zone that is directly interacting with the roots). Hence, the filter bed is naturally aerated. As the water infiltrates it passes several substrate layers with a decreasing grain size over depth (5). Generally, the traditional VSSF-CW filter beds are 100 to 120 centimeters in depth. The filter bed is separated from the surrounding soil by a impervious seal. So, water cannot flow in or out of the filter bed via the adjacent soil. The seal is made of a pressed clay layer, a plastic foil or both. Via the drainage pipe located at the bottom of the VSSF-CW filters (6), the treated waste water flows to a monitor and control well (7). Ultimately, the water can be discharged from the system (8) (Global Wetland Technology, n.d.; Hoorn, 2017; Roest, 2015; Wetlantec BV, n.d.).

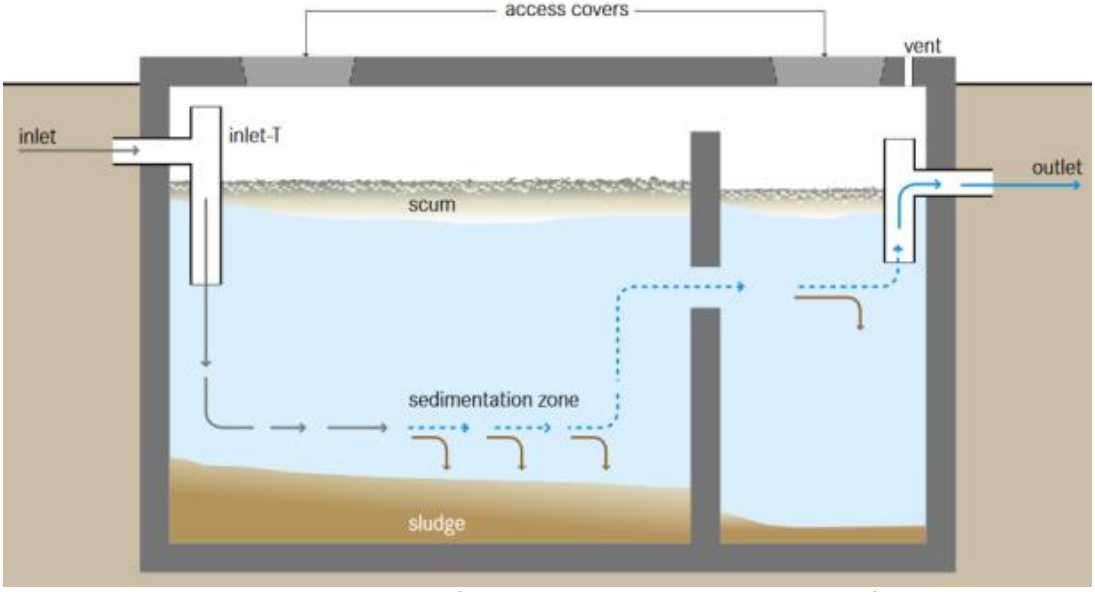

Figure 4.2. Schematic representation of a septic tank. Illustration adapted from Tilley et al. (2014).

4.1.2 Waste water treatment principles

The primary treatment consists of physical and biological processes. In the septic tank and the FOG trap, the physical treatment takes place by entrapment of the settling and floating substances (Figure 4.2 & Figure 4.3). The settled substances form an accumulating sludge layer at the bottom of the septic. As a result of the primary treatment stage, the amount of suspended solids, the BOD and the amount of microbial pathogens are reduced (Tilley et al., 2014).

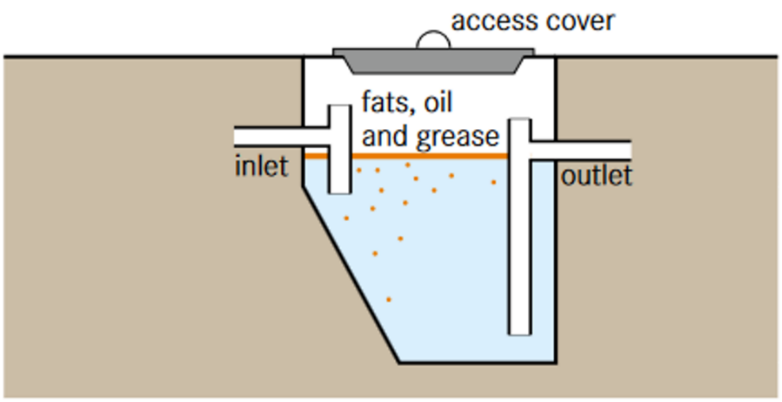

Figure 4.3. Schematic representation of a FOG trap. Illustration adapted from Tilley et al. (2014).

The treatment in the filter bed relies on physical, chemical and biological processes. The physical processes are the filtration of suspended matter and microorganisms by the substrate layers. The chemical treatment processes involve the adsorption and precipitation reactions. Adsorption takes place at the surfaces of the soil grains and the organic material in the soil. As a result, trace elements and phosphates are immobilized (Crites, R., and Tchobanoglous, 1998; Nanninga, 2011; Spoelstra & Truijen, 2010). The removal of phosphates is also achieved by precipitation after irreversible binding with iron, aluminum, calcium or other sediment in the filter bed (Moinier, 2013; Rechenzentrum, n.d.).

Biological processes that contribute to the treatment of waste water in a VSSF-CW are nutrient uptake, bacterial digestion and bacterial degradation. The helophyte plants use the waste water constituents as a source of nitrogen (N) and phosphorous (P), as nutrients for their growth. The nutrients are taken up via the plant roots. The bacterial digestion and degradation take place in the biofilms present on the soil grains and on the plant roots (Nanninga, 2011). In aerobic conditions the bacteria induce the oxidation of organic matter and the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) and nitrite (NO_2^-) (nitrification). In anaerobic conditions the bacteria induce the conversion of NO_3^- and NO_2^- into nitrogen gas (denitrification) (Spoelstra & Truijen, 2010). Compared to other constructed wetland types, the VSSF-CW systems performs well on the removal of NH_4^+. Due to the intermittent character of the waste water supply to the filter bed, the aerobic condition varies over the soil column and is alternating over time. As a result, the nitrification occurs over the entire filter column after every waste water 'batch'. Besides, because the helophytes provide the transport of oxygen from the atmosphere into the rhizosphere, a higher activity of the bacteria in the biofilms and the roots can be found. Hence, improved nitrification and pathogen removal rates take place in the rhizosphere.

Nevertheless, the major limitation of the domestic waste water treatment by traditional VSSF-CW systems is the NO_3^- removal by denitrification (Austin & Yu, 2018; Kadlec & Wallace, 2008; Tilley et al., 2014). In the upper layers of the filter bed, the carbon-rich material is reduced. As a result, a deficiency of carbon in the deeper layers occurs. The denitrifying bacteria are located in the deeper layers and require carbon for their activity. However, the carbon deficiency leads to a limited denitrification rate in the deeper layers. An estimated maximum of 20% to 30% of the NO_3^- is removed by the denitrifying bacteria in the entire filter (Van Oirschot, 2020). Hence, are a high concentration of NO_3^- remains in the effluent.

Last, an important physical factor of the filter bed is the hydraulic retention time (HRT). The HRT is the average length of time that the water is present in the filter bed. In traditional VSSF-CW filters, the HRT is one to a few days. The longer the contaminated water is present in the subsurface, the better the treatment efficiency is. As the hydraulic conductivity decreases at some locations (e.g. due to clogging of the pores), the flow velocity becomes higher at other locations of the filter bed. As a result, the HRT at the columns with a high flow velocity decreases. Hence, the treatment efficiency decreases (Panrare et al., 2015). Helophytes negatively influence the occurrence of clogging. The presence of the roots and the wind-induced movement of the plants facilitate larger pore sizes in the topsoil. Hence, clogging is less likely to occur in the top layer, and the infiltration of waste water is maintained (Nanninga, 2011).

4.1.3 Technological advancements

During the last three decennia, the set-up of the VSSF-CW components made progressive developments in order to improve the treatment performance. A manual for system design and operation by the Dutch Ministry of Housing, Spatial Planning and Environment (VROM) and the Judging Institute for Water Supply Articles (Kiwa) suggests several improvements of the filter substrate. First of all, the VSSF-CW systems occasionally are inconsistent in the removal of phosphates from the waste water. This can be resolved by adding iron or copper containing material to the substrate. The metals increase the capacity of the filter to bind and immobilize phosphates, resulting in reduced phosphate concentration in the effluent (C. A. Arias & Brix, 2005; Vohla et al., 2011; Z. Wang et al., 2013). Additionally, calcium and aluminum enrichment of the soil bed increases the immobilization (by precipitation) of phosphates. In practice, the filter bed can be enriched by the addition of scraps or fillings of the desired metal, metal-enriched sand, or a shell grit layer (for calcium enrichment) (Spoelstra & Truijen, 2010; Vohla et al., 2011). For the addition of iron, the guidelines of VROM and Kiwa (1998) recommend to add 15 kg iron solids (< 1mm) per cubic meter filter bed.

Furthermore, the addition of straw to the substrate is used as a ‘kick-starter’ for the removal of N during the initial stage of the constructed wetland. During that stage, the helophytes and the rhizosphere are not fully developed. Hence, the N removal in the root zone is relatively low. By adding straw to the filter bed, the N removal is promoted due to the additional carbon source for the microorganisms (Rousseau et al., 2004). The Dutch guidelines recommend to add *“one bale straw per 10 m³ sand”* (VROM & Kiwa, 1998). The effect of the straw is only temporal, since the straw decomposes relatively fast.

A more contemporary technological advancement is the forced aeration of the filter bed. Via aeration pipes that are located at the bottom of the filter bed, air is transported into the substrate. As a result, the oxygen demand of the waste water can be met. As a result, the COD and BOD will reduce and the nitrification rates will increase. Besides, the input of air can be controlled and adjusted at any moment. Hence, controlled optimization of the oxygen demand reduction and the nitrification rates are possible with the forced aeration VSSF-CW systems (Boog et al., 2019; Foladori et al., 2013; SSWM, n.d.-a; STOWA, n.d.-a; Van Oirschot, 2020). The depth of the forced aeration VSSF-CW filter is about 0.3 m (Rietland bvba, n.d.-a). Commonly, the substrate material that is used is expanded clay aggregate (STOWA, n.d.-a). The pore spaces of the medium facilitates the ability of the air to travel upwards through the filter bed. Also, the expanded clay aggregate provides more surface area of the substrate for the treatment processes to take place (Van Oirschot, 2020).

4.2 Environmental dimension

The key findings of the assessment of the VSSF-CW technology in the environmental dimension are presented in Table 4-I. The results for the five included assessment aspects are discussed in detail in the following five subsections.

Table 4-I. Overview of the key findings for the product specifications and the actual performance of the VSSF-CW technology in the environmental dimension.

Aspect	Product specifications	Actual performance (All traditional VSSF-CW)
Water treatment efficiency	Effluent quality meets the IBA class IIIb standards.	Effluent quality meets the IBA class IIIb standards.
	NO_3^- removal is limited.	Good overall N removal.
	Pathogen removal > 99%	Pathogen removal of 1.4 - < 4.9 log
	Forced aeration systems have improved BOD and possibly improved N removal.	
	Forced aeration systems have a proper contribution to the removal of pharmaceuticals.	The system in Drielanden has a proper contribution to the removal of pharmaceuticals.
Local water balance	Effluent can be discharged to local surface water.	Effluent is discharged to local surface water.
	Effluent can be reapplied for toilet flushing, showering, laundry, garden irrigation or outside cleaning if the quality is sufficient.	In Polderdrift, the effluent is reapplied for toilet flushing.
Nutrient recovery	Recovery via helophytes harvesting.	Helophytes harvested.
	Reuse as fertilizer is feasible on large scale.	Composted locally or discarded.
Energy balance	Traditional systems: < 4.4 kWh p.e.$^{-1}$ year^{-1}	EVA-Lanxmeer: 14.2 kWh p.e.$^{-1}$ year^{-1}
	Forced aeration systems: 20-30 kWh p.e.$^{-1}$ year^{-1}	
Spatial requirements	Traditional systems: 2.4 – 5 m² p.e.$^{-1}$	Polderdrift: 2.6 m² p.e.$^{-1}$ EVA-Lanxmeer: < 6.5 m² p.e.$^{-1}$ Drielanden: 2.7 m² p.e.$^{-1}$
	Forced aeration systems: 0.75 m² p.e.$^{-1}$	
	Provides opportunities for multi-beneficial integration with local (living) environment.	Contributes to biodiversity.

4.2.1 Water treatment efficiency

Product specifications

In principle, VSSF-CW systems are designed to meet the legal water quality standards. If domestic waste water is treated on small scale, the IBA class IIIb standards apply for the VSSF-CW systems in the Netherlands (see Table 2-I) (VROM & Kiwa, 1998). Dutch system installers Ecofyt and Wetlantec assure that their traditional VSSF-CW system meet these legal standards (Ecofyt, n.d.-a; Wetlantec Nederland B.V., n.d.).

The data found in literature concerning the effluent quality from various VSSF-CW system worldwide are shown in Table 4-II. The data show a wide range of values for the effluent quality parameters. The 132 rural cases are designed to meet these standards. From data of these Dutch rural cases show that the average effluent quality values for most parameters do not meet the legal standards (see Table 2-I). Only the average COD and total suspended solids (TSS) concentrations in the effluent are sufficiently low.

As explained in subsection 4.1.2, the NO_3^- removal is limited in traditional VSSF-CW system. The NO_3^- removal efficiencies of two system set-ups in Manchester (UK) are measured periodically for two years. The NO_3^- removal rates found are on average 34.6% and 15.3%.

Wang et al. (2017) studied the relation between temperature and nitrogen removal rates. They concluded that the bacterial activity that results in nitrification and denitrification is positively correlation with temperature. However, the data of Rozema et al. (2016) observed the contrary (Table 4-II). The differences in treatment efficiency between the coldest and warmest six months per year over a six year period were studied. A major difference can be seen in the NH_4^+ and total Kjeldahl nitrogen (TKN) removal averages. During the period with higher than average temperatures, the nitrogen removal rate was lower. Furthermore, Wu et al. (2011) found no significant variation in treatment removal rates for different temperatures.

Paraskevopoulos (2019) studied the pathogen removal of constructed wetlands. Overall, the VSSF-CW systems removed a higher share of pathogens from wastewater than the FWS-CW and the HSSF-CW systems. The 19 worldwide VSSF-CW systems removed 99 percent of the indicator pathogens on average (see Table 4-II). Besides, García et al. (2008) found a log removal of 2.70 (99.8%) of the total coliforms in waste water treated by subsurface flowing constructed wetlands. They found no significant differences in coliform removal between the winter and summer period.

For forced aeration VSSF-CW systems, the main advantages are the reduction in biochemical oxygen demand and the increasing nitrogen removal rate. The latter is the result of full saturation of the filter column and applying oxygen from the bottom of the bed. By doing so, the aerobic as well as anaerobic processes (i.e. nitrification and denitrification) can take place over the entire column more effectively, including the upper layers where more carbon is available. Hence, denitrification and nitrification rate are less limited, and the TN removal is improved in forced aeration VSSF-CW systems (Austin & Yu, 2018; Van Oirschot, 2020).

Table 4-III shows the data concerning treatment performance of forced aeration VSSF-CW systems. Compared to the performances of traditional VSSSF-CW systems, the data does not show a distinctive improvement of nitrogen removal. Very high BOD and COD reduction performances are found in the treatment efficiency data of forced aeration VSSF-CW systems in Belgium and China.

The removal of pharmaceuticals and pollutants from personal care products by constructed wetlands is relatively unknown. This especially applies for the VSSF-CW systems (Li et al., 2014). Auvinen et al. (2017) and Matamoros et al. (2007) studied the removal efficiencies of forced aeration VSSF-CW systems. Their results are presented in Table 4-IV, including the removal efficiencies of the WWTP in Århus (Denmark) as a comparison. Both studies found that the forced aeration VSSF-CW systems have a proper contribution to the removal of pharmaceuticals. The VSSF-CW system in Århus, Denmark removed 20% of the carbamazepine, while the nearby WWTP removed only 8% of this pollutant. However, the removal efficiencies for all other measured emerging pollutants do not indicate that forced aeration VSSF-CW systems perform better than the WWTP.

Actual performance

The data on treatment performance of the three practical cases are shown in Table 4-V. The data from the effluent in Polderdrift originates from a health risk assessment. Therefore, the measured parameters in Polderdrift differ from the common water quality parameters for waste water treatment. Hence, comparison between the treatment efficiency in Polderdrift and the product specifications is not applicable.

Nanninga (2011) performed effluent quality measurements and removal efficiency calculations for the smallest VSSF-CW systems in EVA-Lanxmeer. The data show that the effluent quality meets all the Dutch legal standards for all parameters (see Table 2-I). Moreover, the low biochemical oxygen demand together with the low dissolved oxygen in the effluent indicate that the degradation of organic matter is near optimal. Remarkable is that the nitrogen removal processes performed also very well. This is in contrast with the expected limitations that are explained in the product specifications paragraph.

Between October 2013 and January 2015 the effluent quality and removal efficiency were monitored in Drielanden. During the monitoring period, an increasing portion of the domestic black water was added to the influent. Overall, the treatment performed sufficient when low portions of the generated black water was added. However, the BOD removal, nitrification processes and removal of E. coli all decreased significantly when more than 60% [c] of the black water was added (Gemeente Groningen, 2016).

Additionally, the removal rate of the total phosphorus (TP) decreased from 90% to 50% over a period of less than two years. Gemeente Groningen (2016) suggests that the phosphorus (P) sorption capacity of the filter decreases over time due to P saturation. The expectation is that the decrease in P removal rate will further decline if no changes are made in the design of the filter substrate (e.g. addition of iron rich substrate matter).

Furthermore, several types of pharmaceutical compounds and trace elements were measured in the VSSF-CW effluent during the monitoring study in Drielanden. The removal rates of the pharmaceutical compounds were relatively high compared to the forced aeration VSSF-CW systems and the WWTP in Denmark (see Table 4-IV). Only for sotalol and atenolol the removal rates of the VSSF-CW system were low compared to the other studies. Besides, for none of the three practical cases the effluent concentrations or removal rates of pollutants from personal care products were found.

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[c] The average generated black water in Drielanden was 18 m^3 day^{-1} during the monitoring period (Gemeente Groningen, 2016). This rate is taken as the 100% portion added.

Table 4-II. Treatment performance data of traditional VSSF-CW systems.

Location	Type of waste water	TSS	BOD_5	COD	NH_4^+	NO_3^-	TN	TP	Coliforms	Remarks	Source
Ontario, Canada **(6 coldest months)**	Municipal WW & Winery waste water									Mean air temperature = 1.4°C	Rozema et al. (2016)
	Removal (%)	97.7	99.9	98.9	98.2	-	98.8[1]	-	-		
	Effluent (mg l⁻¹)	2.9	0.7	14.8	0.02	0.83	0.04[d]	-	-		
(6 warmest months)										Mean air temperature = 17.1°C	
	Removal (%)	98.0	>99	98.9	72.7	-	88.7[1]	-	-		
	Effluent (mg l⁻¹)	2.7	0.1	6	0.18	2.03	0.45[1]	-	-		
Beijing, China	Household waste water (rural)									Air temperatures -7°C to +14°C.	Wu et al. (2011)
	Removal (%)	97	96	-	88.4	-	-	87.8	-	No significant loss of treatment	
	Effluent (mg l⁻¹)	3.7	11.8	-	3.5	-	-	0.6	-	efficiency during winter.	
Manchester, UK	Municipal waste water from combined sewers									Averages over 2 years (all-year round)	Sani et al. (2013)
Set-up 1	*Removal (%)*	89.4	41.9	55.8	73	34.6	-	67.8	-	HRT = 72 h	
	Effluent (mg l⁻¹)	8	-	61	10	-	-	3	-		
Set-up 2	*Removal (%)*	90.8	47.4	57.1	78.1	-	-	71.7	-	HRT = 72 h	
	Effluent (mg l⁻¹)	7	-	59	8	-	-	2	-		
Set-up 3	*Removal (%)*	92.9	64.2	67.6	59.7	15.3	-	72.6	-	HRT = 72 h	
	Effluent (mg l⁻¹)	11	-	92	19	-	-	4	-		
Set-up 4	*Removal (%)*	89	60.6	55.2	79.3	-	-	69.4	-	HRT = 36 h	
	Effluent (mg l⁻¹)	9	-	62	7	-	-	3	-		
Set-up 5	*Removal (%)*	90.9	66.6	57.1	78.5	-	-	71.1	-	HRT = 36 h	
	Effluent (mg l⁻¹)	7	-	58	8	-	-	2	-		
Dutch rural areas	Domestic waste water									Mean values of 132 Dutch projects.	STOWA & Rioned (n.d.-d)
	Effluent (mg l⁻¹)	12.8	43.5	9.4	10	72.1	68.2	6.7	-		
Various cases worldwide	Raw, domestic or and pre-treated waste water									Mean values of 19 cases (16 pilot set-ups; 3 full-scale).	Paraskevopoulos (2019)
	Removal (%)	82.8	93.7	83.4	-	-	-		99.99	HRTs range: 0.01 - 9.1 days	

[d] Amount in Total Kjeldalh nitrogen.

Table 4-III. Summary of treatment performances of forced aeration VSSF-CW systems.

Location		TSS	BOD_5	COD	NH_4^+	NO_3^-	TN	TP	Remarks	Source
Århus, Denmark	*Removal (%)*	84			86				Raw urban waste water	Matamoros et al. (2007)
	Effluent (mg l^{-1})	15.1	10.7		8.1					
Aalbeke, Belgium	*Effluent (mg l^{-1})*			25.8 - 28.8	0.0 - 5.6	15.1 - 21.1			Communal waste water	
Groeninge, Belgium	*Effluent (mg l^{-1})*			25.8 - 113	0.0 - 1.8	21.1 - 125			Hospital effluent	
Yangling, China	*Removal (%)*			98.5	69.5		74.7		Synthetic waste water; Optimization set-up; HRT = 72 h	Zhou et al. (2018)
Antwerp, Belgium	*Effluent (mg l^{-1})*	< 2	< 3	13	0.4		1.7	0.77	Sanitary waste water from office building	Van Oirschot (n.d.)
Lendelede, Belgium	*Removal (%)*	92	100	98			66	96%	Industrial waste water;	Van Oirschot (n.d.)
	Effluent (mg l^{-1})	12	14	105			< 2	0.17	Loading rate = 12 - 24 mm d^{-1}	

Table 4-IV. Treatment performance for pharmaceutical compounds and personal care products.

Source	Auvinen et al. (2017)	Matamoros et al. (2007)		Gemeente Groningen (2016)	
Treatment system	Forced aeration VSSF-CW	Forced aeration VSSF-CW	Conventional WWTP	Traditional VSSF-CW	
Location	Aalbeke and Groeninge, Belgium	Århus, Denmark	Århus, Denmark	Drielanden, the Netherlands	
Waste water type	Communal & hospital effluent	Communal	Communal	Domestic	
HRT	12 - 24 h	137 h	-	?	
	Removal (%)	*Removal (%)*	*Removal (%)*	*Removal (%)*	*Effluent (µg/l)*
pharmaceuticals					
salicylic acid	-	85	99	-	-
ibuprofen	-	55	60 - 70	80	1.1
OH-ibuprofen	-	51	95	-	-
CA-ibuprofen	-	71	95	-	-
naproxen	-	62	40 - 55	80	0.8
diclofenac	17 - 30	53	9 - 75	50	0.04
carbamazepine	0 - 12	20	8	14	0.6
caffeine	-	82	99	98	6
metformin	98 - 100	-	-	-	-
sotalol	18 - 32	-	-	negligible	0.2
valsartan	99 - 100	-	-	-	-
atenolol	82 - 95	-	-	43	0.04
bisoprolol	69 - 82	-	-	-	-
gabapentin	37 - 40	-	-	-	-
sulfamethoxazole	50 - 76	-	-	-	< 0.05
personal care products					
methyl-dihydrojasmonate	-	78	98	-	-
hydrocinnamic acid	-	82	-	-	-
oxybenzone	-	88	68 - 99	-	-
galaxolide	-	88	70 - 85	-	-
tonalide	-	75	75 - 90	-	-

Table 4-V. Treatment performance data of the three practical cases.

Location	Polderdrift		EVA-Lanxmeer (VSSF-CW located in the North-West)			Drielanden		
Source	Van Betuw (2005)		Nanninga, (2011)			Gemeente Groningen (2016)		
Quality parameter	***Effluent***	***Unit***	***Effluent***	***Unit***	***Removal (%)***	***Effluent***	***Unit***	***Removal (%)***
Dissolved oxygen			0.9 – 1.8	mg l^{-1}				
TSS			6.6 - 13	mg l^{-1}	75.0 – 87.3	3.2 ± 4.7	mg l^{-1}	91%
Acidity	7.55	pH	6.84 – 7.09	pH		7.2 ± 0.1	pH	Difference = -0.1
Chlorine	11	mg l^{-1}				54 ± 9	mg l^{-1}	19%
Aggressive carbonic acid	< 0.5	mg l^{-1}						
Hydrogen carbonate	120	mg l^{-1}						
NH_4^+			0.30 – 0.35	mg l^{-1}	93.4 – 94.5	4.4 ± 7.5	mg l^{-1}	76%
TKN			0.5 – 1.4	mg l^{-1}	87.3 – 95.5	5.6 ± 9.9	mg l^{-1}	82%
Organic bound N						2.0 ± 2.9	mg l^{-1}	86%
NO_2^-			< 0.01	mg l^{-1}	-	0.08 ± 0.07	mg l^{-1}	11%
NO_3^-			< 0.05	mg l^{-1}	-	6.9 ± 5.9	mg l^{-1}	-
TN			0.56 – 1.46	mg l^{-1}	86.8 – 95.0	13 ± 11	mg l^{-1}	58%
TP			0.13 – 0.16	mg l^{-1}	95.9 – 97.5	1.0 ± 1.2	mg l^{-1}	76%
Sulfate	10	mg l^{-1}						
Arsenic						< 10	µg l^{-1}	-
Cadmium						0.1 ± 0.1	µg l^{-1}	50%
Chromium						1.2 ± 0.8	µg l^{-1}	33%
Copper						12 ± 9	µg l^{-1}	89%
Iron	0.37	mg l^{-1}						
Manganese	<0.01	mg l^{-1}						
Mercury						< 0.15	µg l^{-1}	-
Lead						< 5	µg l^{-1}	-
Nickel						< 10	µg l^{-1}	-
Zinc						21 ± 14	µg l^{-1}	83%
COD			13 - 19	mg l^{-1}	93.6 – 95.9	25 ± 12	mg l^{-1}	95%
BOD_5			<1.2	mg l^{-1}	99.3 - > 99.5	3.7 ± 2.8	mg l^{-1}	98%
E.coli	250	cfu/100ml	$<1.5\times10^1 – 1.62\times10^2$	cfu/ 100ml	3.8 - > 4.9 log	$8.4 \pm 2.1 \times10^4$	cfu/ 100ml	1.4 log
Aeromanas species (30°C)	80	cfu/100ml						
Bacteriophages						$2.1 \pm 1.9 \times10^3$	pfu/l	3.8 log

4.2.2 Local water balance

Product specifications

As the effluent meets the quality standards, it can be discharged to a surface water body. In the Netherlands, the near-urban surface water bodies are often directly connected to large surface water bodies that eventually discharge to the North Sea or the Wadden Sea. However, the effluent can also be reused on local scale. Several VSSF-CW effluent reuse options are proposed for domestic application. The treated water can be transported back to the households for the applications of toilet flushing, showering, laundry, garden irrigation or outside cleaning (e.g. car washing or hosing down urban structures). A significant share of the potable water use might be avoided by supplying these household water applications with reclaimed waste water from a local treatment system (STOWA & Rioned, n.d.-d).

However, the quality of the effluent is of major importance for the reuse potentials. Especially the risk of harmful impacts to human health, human comfort and environment are assessed when considering the reuse of waste water in households (STIBA, 1998). Nevertheless, no health-based water quality criteria have been set for the local reuse of waste water (Schets et al., 2017). To improve the quality of the reclaimed water, the VSSF-CW system can be complemented with a tertiary treatment step. Mostly, a sediment trap is included to catch discharged particles from the filter substrate. Furthermore, the treatment can be complemented with for instance UV-radiation, chlorination or active carbon filtration. The design of the tertiary treatment depends on the reuse application considered (Van Oirschot, 2020).

Moreover, the VSSF-CW system is subject to climatic influences. The effects of precipitation and evaporation to the water balance are explained in Appendix 2.

Actual performance

The effluent of the VSSF-CW system in Polderdrift returns to the toilets in the residences. First, the effluent flows via a sediment trap to the effluent collection well. The effluent generation rate is 6.4 $m^3\ d^{-1}$ (Boano et al., 2019). Subsequently, the water is transported through pressure lines to the houses for toilet flushing. If the demand for toilet flush water is higher than the generated VSSF-CW effluent, the collection well is supplemented with potable water (Van Betuw, 2005). If the collection well is full and effluent still generated, the surplus is directly discharged to a local surface water body (Coopmans & Van Ruijven, 2020; Van Betuw, 2005). The volumetric performance of the reused water is not documented. However, the amount of added potable water is approximately 3 $m^3\ d^{-1}$. Per residents that is 34.1 l d^{-1}liter. Compared to the average Dutch water use for toilet flushing (see Table 2-II), this is similar amount. This indicates that the reused effluent contributes only a small share of the water supply to the toilets (Coopmans & Van Ruijven, 2020).

In EVA-Lanxmeer, the three VSSF-CW systems have a designed grey water treatment capacity of 32 l $m^{-2}\ d^{-1}$. After treatment, the effluent is discharged to local surface water bodies (Nanninga, 2011). The amount of actually generated effluent is unknown.

In Drielanden approximately 42 m³ d^{-1} waste water is treated by the VSSF-CW system. The VSSF-CW effluent flows to a FWS-CW system for additional treatment. After the FWS-CW treatment, the effluent is discharged to the local surface water bodies (Gemeente Groningen, 2016).

4.2.3 Nutrient recovery

Product specifications

Nutrients that are removed in a VSSF-CW filter can be recovered by harvesting the growing helophytes. In fact, if the helophytes are not harvested, the plant material will decompose on the filter surface. As a result, the nutrients are recycled into the filter system, which counteracts the nutrient removal from the waste water (Van Oirschot, 2020).

Since the plant material contains nutrients that are required for plant growth, the harvested biomass can eventually be used for the fertilization of soils (Verhofstad et al., 2017). The harvested material needs to be composted for this. If the helophytes are harvested on small scale, the application options are limited to a local scale (Quilliam et al., 2015).

Actual performance

The helophytes are periodically mowed in all three practical cases. During a field visit in Polderdrift, a communal compost bin for green waste was observed near the VSSF-CW system (Appendix 5). However, it is not clear if the clippings from the helophytes end up in this bin. In EVA-Lanxmeer and Drielanden, the clippings from the periodic mowing activities are discarded off via waste management organizations (Nanninga, 2011). Although the biomass is not reapplied on local scale, the green waste is centrally composted or converted into energy (Rijkswaterstaat, 2019).

4.2.4 Energy balance

Product specifications

The VSSF-CW is regarded as an energy efficient waste water treatment technology. In a typical system, only the waste water distribution pumps require energy (electricity). Kadlec & Wallace (2008) state that the VSSF-CW system is one of the most energy efficient technologies for waste water treatment. The energy consumption per volume of treated waste water is estimated to be less than 0.1 kilowatt-hours (kWh) m^{-3}. With a waste water production of 119.2 liter p.e.$^{-1}$ d^{-1}, the energy consumption amounts to 4.4 kWh p.e.$^{-1}$ year^{-1} in the Netherlands. Dutch constructed wetland installer Wetlantec provides a similar estimation in its brochure (Wetlantec Nederland B.V., n.d.).

Because of the additional air supply component, forced aeration VSSF-CW systems generally consume more energy than the traditional VSSF-CW systems. According to Van Oirschot (2020), the forced aeration system of Rietland bvba consumes 20 to 30 kWh p.e.$^{-1}$ year^{-1}.

Table 4-VI shows the estimations for the specific energy consumption of the VSSF-CW systems. As a comparison, the specific energy consumption of the average Dutch WWTP is added. According to GMB (2017) the annual energy consumption of the average Dutch WWTP ranged from 26.3 to 30.6 kWh p.e.$^{-1}$ between 2006 and 2015.

Table 4-VI. Estimated specific energy consumption of the traditional and forced aeration VSSF-CW system and a Dutch WWTP in kWh p.e.$^{-1}$ year^{-1}.

Technology	Specific energy consumption	Source
Traditional VSSF-CW	< 4.4	Kadlec & Wallace(2008); Wetlantec Nederland B.V. (n.d.)
Forced Aeration VSSF-CW	20 - 30	Van Oirschot (2020)
Dutch WWTP	26.3 – 30.6	GMB (2017)

Actual performance

An indication of the actual energy consumption could only be deduced from the 2010-electricity bill of EVA-Lanxmeer. The electricity bill totaled a €1,500 for the three waste water pumps (Nanninga, 2011). During 2010, the consumer price for electricity from the grid was €0.176 per kWh in the Netherlands (CBS, 2016). Based on that price, the VSSF-CW system in EVA-Lanxmeer consumed approximately 8,523 kWh in 2010. For each resident that was connected during that year[e], 14.2 kWh is consumed for the grey water treatment.

For the other cases no data concerning the energy consumption of the VSSF-CW systems was found.

4.2.5 Spatial requirements

Product specifications

In urban context, the spatial requirement of the waste water treatment facility is an important specification. When designing a constructed wetland for urban waste water treatment, the spatial requirement is commonly a limiting factor. Compared to other types of constructed wetlands, the VSSF-CW technology appears to have low spatial requirement (Rousseau et al., 2004). Therefore, it is the most popular option of constructed wetlands for waste water treatment in urban areas. Dutch VSSF-CW installers estimate that 3 to 5 m² of filter bed is required for each p.e. in order to meet the Dutch legal effluent quality standards (Ecofyt, n.d.-b; Rietland bvba, n.d.-e; Wetlantec Nederland B.V., n.d.). In practice, VSSF-CW systems are designed for treating the waste water of 2 to 5000 p.e. (Wetlantec Nederland B.V., n.d.). When installing VSSF-CW systems with a larger total treatment capacity, the required area of filter bed tends to be relatively low (3 m² p.e.$^{-1}$). Rousseau et al. (2004), analyzed the constructed wetlands in Flanders (Belgium). They computed that VSSF-CW systems for treatment of domestic waste water have on average a spatial requirement of 3.8 m² p.e.$^{-1}$, with an average design capacity of 158 p.e. (n=34). The year of installment of these VSSF-CWs range from 1986 to 2004. According to Van Oirschot (2020), 1 m² of filter bed is able to treat about 50 liter domestic waste

[e] Approximately 600 residents were connected to the VSSF-CW in 2010 (Nanninga, 2011).

water per day. This specific capacity applies for modern non-aerated VSSF-CW systems with a relatively large total design capacity. Considering the 119.2 liter waste water generation per Dutch resident, approximately 2.4 m² p.e.$^{-1}$ is required.

Although constructed wetlands require more space than other waste water treatment technologies, the used space still holds some potential benefits. Especially the vegetation on top of the filter beds contribute to the additional values of constructed wetlands. This applies for VSSF-CW systems as well. Stefanakis (2019), discusses the opportunities of constructed wetlands for the promotion of urban biodiversity, the control of rainwater runoff, reduction of the heat island effect and social benefits from the aesthetics and educational values. Therefore, VSSF-CW systems have the potential for multi-beneficial integration in urban planning.

The main advantage of forced aeration VSSF-CW systems is that the spatial requirements are strongly reduced. The Phytoair technology of Rietland BV requires 0.75 m² p.e.$^{-1}$ (Van Oirschot, 2020). Furthermore, the quality change of the used surface area differs from the quality change of the used surface area of traditional VSSF-CW systems. Since no helophyte plants are required, the surface area can be covered with other types of vegetation. Therefore, a urban spatial planner may choose for the desired vegetation. Also, the Phytoair technology can be integrated with other types of land use. For example, the VSSF-CW system can be covered with grass and used as a car parking space (Rietland bvba, n.d.-c, n.d.-b). Land uses as urban green spaces or semi-paved sidewalks are possible options as well when using forced aeration VSSF-CW systems (Van Oirschot, 2020).

Actual performance

Table 4-VII presents the data concerning the spatial requirements of the three Dutch practical cases. The used surface areas for the VSSF-CW systems in Polderdrift, EVA-Lanxmeer and Drielanden is 230 m², 4300 m² and 1000 m², respectively. Considering the estimated residents that are connected to each system, the spatial requirement is 2.6 m² p.e.$^{-1}$ in Polderdrift, at most 6.5 m² p.e.$^{-1}$ in EVA-Lanxmeer and 2.7 m² p.e.$^{-1}$ in Drielanden. Note that in EVA-Lanxmeer the design capacity is considerably larger than the amount of households actually connected. Therefore, the operational spatial requirement per p.e. is substantively higher than in the two other cases, although the designed spatial requirement was around 3.9 m² p.e.$^{-1}$. The specific spatial requirement in Polderdrift and Drielanden are slightly lower than the values that are described in the product specifications. Furthermore, no indication of the relation between treatment capacity size and the specific spatial requirement could be deduced from these data.

The changes found in quality of space in the three neighborhoods match some of the product specifications. Changes in biodiversity are indicated by observations of a rare dragonfly (*Aeshna viridis*) and its larvae on the helophytes in Drielanden (Bewonersvereniging Drielanden, 2018) and observations of emerging flowers and birds near the VSSF-CWs in Polderdrift and EVA-Lanxmeer (Nanninga, 2011). Additionally, the quality of the space has increased in the view of the residents of Polderdrift. Mr. Coopmans and Mr. Van Ruijven both agree about the better living-environment compared to other neighborhood without a nature-based water system visual between the houses. According to the men, the local decentralized water system contributes to a pleasant and calm neighborhood (Coopmans & Van Ruijven, 2020).

Furthermore, no indications are found in the practical cases for the contribution of VSSF-CW to rainwater runoff control or reduction of the heat island effect.

Table 4-VII. Data of the spatial requirements of the VSSF-CW systems and the connected residents. Data from Coopmans & Van Ruijven (2020), Gemeente Groningen (2016), T. A. Nanninga (2011) and Terra Bella (n.d.).

	Polderdrift	**EVA-Lanxmeer**	**Drielanden**
Design capacity (households)	40	500	-
Connected households	40	> 300	166
Connected residents (p.e.)[f]	88	> 660	365
Surface area VSSF-CW (m^2)	230	4300	1000
Specific spatial requirement (m^2 $p.e.^{-1}$)	2.6	< 6.5	2.7

[f] Based on the Dutch average of 2.2 p.e. per household.

4.3 Functional dimension

The key findings of the assessment of the VSSF-CW technology in the functional dimension are presented in Table 4-VIII. The results for the two included assessment aspects are discussed in detail in the following two subsections.

Table 4-VIII. Overview of the key findings for the product specifications and actual performance of the VSSF-CW technology in the functional dimension.

Aspect	Product specifications	Actual performance (All traditional VSSF-CW)
Durability and reliability	Life time expectancy of.. - traditional systems: 25 year. - forced aeration systems: 35 years.	Current time in operation 8 to 24 years.
	Traditional systems are prone to clogging.	Multiple errors in the various system components (clogging, leakages, system regulation, weeds).
	Resilient to climatic influences.	
		Operation in Polderdrift is halted due to end-user sentiment (fear of risk to human health).
Operation and maintenance (O&M)	Traditional system: relatively easy O&M, no high skill level required.	Residents are able to perform daily operation and several semi-annual maintenance activities.
		Some maintenance activities are outsourced due to specific requirements (e.g. rinsing of components and research).
	Traditional system: Guidelines for periodic O&M activities provided.	
	Forced aeration systems: Similar O&M activities; higher-level skills required for maintenance of air supply system.	

4.3.1 Durability and reliability

Product specifications

The water distribution pumps are the only moving components of the VSSF-CW technology. Therefore, the technology has little opportunity to wear down. As a result, the technology has a long overall longevity and low operational requirements (Rietland bvba, n.d.-d; SSWM, n.d.-b). According to Dutch system installer Ecofyt (n.d.), the constructed wetlands may operate adequately for more than 25 years. A forced aeration VSSF-CW even has a longer live expectancy: 35 years. Yet, no forced aeration systems exists that are already in operation for this long (STOWA, n.d.-b).

Nevertheless, Van Oirschot (2020) mentions that the waste water distribution pumps in a traditional VSSF-CW assumable have a longevity of eight to ten years. Hence, the pumps require replacements two or three times during the life time of the VSSF-CW system. Provided that installment is done correctly and O&M is performed adequately, other system components are expected to endure the entire life time.

The main limitation for the functionality of the VSSF-CW is that the filter bed and the distribution pipes are prone to clogging (Hoffmann et al., 2011; Tilley et al., 2014). The mechanisms of filter clogging and possible solutions are explained in Appendix 3.

Since the VSSF-CW is subject to climatic influences, the concerns arise about the technical consistency of the filter bed over the seasons. However, the VSSF-CW is regarded as a robust technology, which performs continuously over the seasons (Ecofyt, n.d.-b; SSWM, n.d.-b). The seasonal robustness is explained in Appendix 2.

Actual performance

The VSSF-CW systems in the practical cases are currently 24 years (Polderdrift), 17 years (EVA-Lanxmeer) and 8 years (Drielanden) in operation. In general, all system function all year round and perform properly (Gemeente Groningen, 2016; Nanninga, 2011). In this study, no difficulties related to seasonal climatic influences were found.

Major reconstructions of the system during the operational years were only made in Polderdrift. In 2002 or 2003, the VSSF-CW system started to generate very little amount of effluent (Nanninga, 2011). First the pipelines, pumps and wells were investigated for leakage by several parties. When no cause could be allocated, the only reasonable option was to dig through the filter bed for further investigation. That showed that the pressed-clay seal at the bottom of the filter bed was leaking. During the resulting renovation in 2011, the impervious clay layer was restored and supplemented with a plastic foil to prevent future leakage. Since then, no leakage through the bottom of the filter bed has been observed (Coopmans & Van Ruijven, 2020; Nanninga, 2011).

During the reconstruction, the deeper substrate layer was adjusted in such a way that a constant minimum amount of water would be present. This was performed in order to continuously provide water to the helophytes. Prior to the renovation, the helophytes didn't grow sufficiently due to a lack of water in the filter bed (Hoorn, 2017). Furthermore, a layer of iron fillings was added in order to promote the removal of phosphates. However, the filter bed clogged after several months. Precipitated iron oxide blocked the infiltration and drainage, resulting in ponding waste water on the surface. Approximately nine months after the second renovation, this error was resolved (Coopmans & Van Ruijven, 2020).

Besides, faulty constructions were made in the sewers and pre-treatment systems. Too narrow pipelines, and too sharp curves in the pipeline system led to system clogging and sewage overflows in Polderdrift (Coopmans & Van Ruijven, 2020; Nanninga, 2011). In Drielanden the distribution pumps got blocked by moist wipes that were flushed down the toilets by the residents (Gemeente Groningen, 2016).

Moreover, the regulation and timing of the influent pumps of the VSSF-CW systems in Polderdrift and in EVA-Lanxmeer have been adjusted. In Polderdrift, initially automatic float valves in the influent collection well were installed to regulate the moments of waste water supply to the filter. However, the malfunctioning of these float valves led to a batch of waste water supply every 15 to 30 minutes, which flooded the VSSF-CW filter bed. In EVA-Lanxmeer, few inconveniences have occurred with waste water ponding and poor helophyte growth. The pump regulation is adjusted several times to fit the most appropriate scheme (Nanninga, 2011).

Also in Polderdrift and EVA-Lanxmeer, excessive growth of weeds and grasses occurs between the helophytes. A possible reason for this is the wrongfully preserved distance between the helophytes during installment (Van Oirschot, 2020).

During this study, the operation of the VSSF-CW system in Polderdrift was halted for several months due to fear for public health risks (see subsection 4.5.2). During this period, the helophytes were manually irrigated. Nevertheless, the height of the helophytes is significantly less compared to a typical year (Coopmans & Van Ruijven, 2020). What the effects of the relatively long lasting interruption of the waste water supply is to the functionality of the VSSF-CW is uncertain. However, according to Van Oirschot (2020) a VSSF-CW system is robust enough to function properly almost immediately after being halted for several months. Rainfall and irrigation provide the system with sufficient amounts of water, and the bacteria can feed on nutrient reserves in the soil bed.

4.3.2 Operation and maintenance

Product specifications

The operation and maintenance (O&M) of VSSF-CW systems are regarded as relatively easy and no extraordinary skill level is required for the everyday activities. In practice, most activities can be performed by the end-user with moderate knowledge of the system (Van Oirschot, 2020), especially if it concerns a small-scale VSSF-CW system (SSWM, n.d.-b).

Ministry VROM and Kiwa (1998) created a set of guidelines for the O&M of VSSF-CW in the Netherlands. The guidelines include a set of weekly, quarterly, semi-annual and annual activities that are required to be performed by the responsible actor. The weekly activities mainly exist of checking the state of the system by examining the technology components and, if required, performing low-effort maintenance task. The quarterly and semi-annual activities exist of examination activities as well. However, these concern the less accessible built-in components such as the filters in the FOG trap and the septic tank. If needed, additional maintenance actions must be taken by the responsible actor. On yearly basis, the technology installer is responsible for a complete system check and the maintenance of all components. Furthermore, the helophytes require annual mowing. This should be done during spring, since the vegetation provides the frost prevention of the soil bed. The annual mowing is needed to prevent the filter bed to clog from accumulated dead plant material. Besides, harvesting the helophytes is required to remove the nutrients from the treatment system (Van Oirschot, 2020). The recommended O&M activities are shown in Table 4-IX.

The O&M requirements of forced aeration VSSF-CW systems are similar to those of traditional VSSF-CW systems. However, the technological hardware of aerated system is more complex. Therefore, higher-skill labor is required to perform the O&M activities properly. That applies in particular for maintaining the air distribution system and for the operation of the manually adjustable air supply (SSWM, n.d.-a).

Table 4-IX. Operation and maintenance activities for a VSSF-CW technology. The table is based on the information from Spoelstra & Truijen (2010), Van Oirschot (2020) and VROM & Kiwa (1998).

Frequency	Activity	Additional action
Weekly	Examination of effluent turbidity and smell in monitor well.	
Weekly	Visual check if influent in waste water well (or septic tank) has floating substances or deposition on the edges of the well.	If so, cleaning of the waste water well.
Weekly	Verification of the correct functioning of the pump control system and the user-interface.	
Weekly	Quick-scan of the condition of the entire system.	
Weekly	Visual check if plants other than helophytes are growing on the VSSF-CW surface.	Removal of undesired plants (mainly weeds and grasses).
Weekly (during growing season)	Monitoring of conditions and growing progress of helophytes.	
Weekly (during periods of extreme frost)	If the filter bed tends to freeze, cover of the VSSF-CW surface with agricultural foil for a maximum of two weeks.	
Quarterly	Removal of floating substances from the FOG-trap.	
Quarterly	Removal of accumulated sludge from the septic tank.	
Quarterly	Examination of filter embankments. No rainwater should run-off onto the VSSF-CW surface.	
Quarterly	Examination of the waste water distribution over the surface.	If the distribution is not uniform, the distribution pipes probable need to be flushed. Usually this is required once a year.
Semi-annual	Check of the accumulated sludge in the septic tank. If the settled sludge layer or the floating sludge layer is higher than 30% of the total content height, there is a disturbance in the biological pre-treatment.	
Annual	Complete system check and the maintenance of all components by the installer. If required, the week operator should provide guidance.	
Annual	Mowing of the helophytes during spring.	

Actual performance

In Polderdrift, the most frequent O&M activities are executed by inhabitant Mr. Van Ruijven. Every week he performs a control check of the system component, he records basic data, and, if necessary, he weeds the emerging weeds. Additionally, the 'green group'[9] of Polderdrift organizes a (semi-)annual event where the residents can join and help with weeding and mowing of the filter bed. Several other less frequent activities are under the responsibility of the housing corporation. The housing corporation outsources the annual flushing of the waste water distribution pipes to Rietland bvba, and the semi-annual rinsing of the septic tank and grey water sewers to a sewer cleaning company. However, the assistance of Mr. Van Ruijven is required, since the housing corporation and sewer cleaners do not have the specific knowledge of the VSSF-CW system in Polderdrift (Coopmans & Van Ruijven, 2020).

In EVA-Lanxmeer also a community cooperative exists that focuses on the maintenance of green spaces in the neighborhood. This cooperative is called Stichting Terra Bella. For the VSSF-CW systems they weed the weeds on and around

[9] The green group is a community cooperative that takes the responsibility for the maintenance of the urban green spaces in the Polderdrift neighborhood (Coopmans & Van Ruijven, 2020).

the filter beds 10 times a year, and mow the helophytes during fall. Furthermore, the municipality is responsible for the remaining majority O&M activities. These activities include the twice-annual pruning of the helophytes in June and September, and maintenance and reparation of system components whenever it is necessary (Terra Bella, n.d.). The residents perform the general monitoring of the system and its functioning. If system error occur or maintenance is required, they warn the responsible person of the municipality (Nanninga, 2011).

During the construction of the Drielanden neighborhood in the early 1990s, a separated sewage system was already implemented. The black water sewers are located on private land. Therefore, the residents were responsible for the O&M of the black water sewers. However, O&M was not adequately organized and performed by the residents. This led to frequent clogging and sewage overflow. The reason for the inadequate performance of the O&M by the residents was the weakening sense of responsibility over time. Apparently, the responsibilities of the O&M activities were not fully taken over by successive generations of inhabitants in the Drielanden residences. As a solution, the O&M responsibilities were adopted by the municipality since the implementation of the VSSF-CW system in 2012. Since then, the clogging and sewage overflow have decreased. All other O&M activities are under the responsibility of the municipality as well (Gemeente Groningen, 2016).

4.4 Economic dimension

The key findings of the assessment of the VSSF-CW technology in the economic dimension are presented in Table 4-X. The results for the two included assessment aspects are discussed in detail in the following two subsections.

Table 4-X. Overview of the key findings for the product specifications and actual performance of the VSSF-CW technology in the economic dimension.

Aspect	Product specifications		Actual performance (All traditional VSSF-CW)	
Investment costs	Traditional system:	€411-507 p.e.$^{-1}$	Initial investment in EVA-Lanxmeer:	€681 p.e.$^{-1}$
	Forced aeration system:	€92-408 p.e.$^{-1}$		
Operational costs	Traditional system (annually) - O&M: - Energy:	 €6-40 p.e.$^{-1}$ < €1 p.e.$^{-1}$	Normal annual O&M and energy costs - Polderdrift: - EVA-Lanxmeer:	 €16-50 p.e.$^{-1}$ €33 p.e.$^{-1}$
			One-time research costs Polderdrift:	€48 p.e.$^{-1}$
			One-time component replacement costs - Polderdrift: - EVA-Lanxmeer:	 €114 p.e.$^{-1}$ €31 p.e.$^{-1}$
	Forced aeration system (annually) - O&M: - Energy:	 €15-22 p.e.$^{-1}$ €4-7 p.e.$^{-1}$		

4.4.1 Investment costs

Product specifications

Rousseau et al. (2004) studied the costs of 34 VSSF-CW systems in Flanders (Belgium) that were installed between 1986 and 2003. The treatment capacity of the VSSF-CW ranged from 2 to 2000 p.e., with an average capacity of 158 p.e. (3.8 m^2 p.e.$^{-1}$). The average investment costs were €507 p.e.$^{-1}$. Furthermore, construction costs of a VSSF-CW system treating domestic waste water for 1000 p.e. in Gomati (Greece) were estimated to be €411 p.e.$^{-1}$ (Sihrintzis et al., 2007).

In comparison with the traditional VSSF-CW system, the forced aeration VSSF-CW systems come with lower construction costs. The Sustainable Sanitation and Water Management organization explains that this is mainly the result of the significantly fewer surface area requirement. The estimations for the construction costs of forced aeration VSSF-CW system range from €150 to €200 per p.e. for small and medium-sized systems (SSWM, n.d.-a). However, Labella et al. (2015) provide the construction costs of 100 p.e., 500 p.e. and 1000 p.e. forced aeration VSSF-CW systems in Spain and in the United Kingdom (UK). In Spain the construction costs amount to €94, €116 and €116 per p.e., respectively. In the UK the construction costs amount to €408, €244 and €206 per p.e., respectively. Furthermore, the expanded clay aggregate that is used for the forced aeration VSSF-CW has a similar purchase price as a traditional sand and grit substrate filter bed (Van Oirschot, 2020).

Compared to the construction costs of a WWTP in the Netherlands, the traditional and forced aeration VSSF-CW system might be considerably less expensive. However, the life expectancy of this WWTP is 50 years, which is possibly twice the life time of a VSSF-CW system. The found cost ranges for construction of the VSSF-CW types and the WWTP are presented in Table 4-XI.

Among technology experts, there is a shared belief that the economy of scale advantage applies to the investment costs of the VSSF-CW technology. The larger the capacity of the VSSF-CW system, the lower the investment costs per p.e. tend to be. This seems to actually apply for both traditional and forced aeration VSSF-CW systems (GROENBLAUW, n.d.; Kilian Water, n.d.-a; Roest, 2015; Rousseau et al., 2004; Van Oirschot, 2020). Although, the estimated construction costs of the forced aeration system in Spain doesn't show this relation (Labella et al., 2015).

Actual performance

Of the three practical cases, only the construction costs of the VSSF-CW system in EVA-Lanxmeer are known precisely. A total of €450,000 was invested. The costs can be split into the costs for the filter (€350,000) and the costs for the pumps and wells (€100,000) (Nanninga, 2011). Divided over the estimated 660 residents that are connected to the VSSF-CW systems, the specific construction costs were €681.20 p.e.$^{-1}$.

For Polderdrift and Drielanden specifics on the construction costs aren't found. Although, a speculative amount of fl. 500,000[h] to fl. 600,000 is doing the rounds for Polderdrift (Coopmans & Van Ruijven, 2020; Hoorn, 2017; Nanninga, 2011).

4.4.2 Operational costs

Product specifications

The operational costs of a VSSF-CW system are determined by the O&M activities that are required for proper performance of the technology. The annual operational costs for a VSSF-CW system are estimated around €40 p.e.$^{-1}$. The majority of the costs are for cleaning the system hardware (Rombout et al., 2007; Spoelstra & Truijen, 2010). Meanwhile, Sihrintzis et al. (2007) calculated the annual amount €6 p.e.$^{-1}$ for the entire O&M of the VSSF-CW system in Gomati. According to (SSWM, n.d.-a), the operational costs for forced aeration VSSF-CW systems in developed countries range from €15 to €22.

The operational costs are roughly similar to those of Dutch WWTPs. The average operational costs of the 17 communal WWTPs of the Dutch water board Scheldestromen are €26 p.e.$^{-1}$ (Waterschap Scheldestromen, 2016). The operational costs of the traditional VSSF-CW systems, forced aeration VSSF-CW systems and the Dutch WWTPs are shown in Table 4-XI.

Additional to the operational costs, are the costs for the energy consumption. The expected costs for the energy consumption were calculated[i] and presented in Table 4-XI as well.

[h] Amount in Dutch Guilder (fl.).

Table 4-XI. Cost ranges of the traditional VSSF-CW system, the forced aeration VSSF-CW system and a Dutch WWTP.

Technology	Cost item	Costs (€ p.e.$^{-1}$)	Source
Traditional VSSF-CW	Construction	411 - 507	(Rousseau et al., 2004; Sihrintzis et al., 2007)
	Annual O&M	6 - 40	(Rombout et al., 2007; Sihrintzis et al., 2007)
	Annual energy use	< 0.97	(Kadlec & Wallace, 2008; Wetlantec Nederland B.V., n.d.)
Forced aeration VSSF-CW	Construction	92 - 408	(Labella et al., 2015; SSWM, n.d.-a)
	Annual O&M	15 - 22	(SSWM, n.d.-a)
	Annual energy use	4.40 – 6.60	(Van Oirschot, 2020)
Conventional WWTP (30,000 p.e.)	Construction	1778	(De Graaf, 2018)
	Annual O&M	28.29	(De Graaf, 2018)
	Annual energy use	3.50 – 6.70	(GMB, 2017; Waterschap Scheldestromen, 2016)

Actual performance

In Polderdrift, the operational costs consist of costs for the cleaning of system components (e.g. sewers, wells, distribution pipes), water bills and energy bills. The water bills are included because of the required addition of potable water to the effluent well, which is used for flushing the toilets. Between 2002 and 2009 the total operational costs fluctuated between €1,383 and €4,382 for the entire wastewater system. The average operational costs over these eight years were €2,640. The relatively large fluctuations could probably be explained by the leakages of the water through the bottom of the filter bed. Because of this, more potable water additions were made to comply with the water demand of the toilets. Up to 2 m² of potable water was added every day (Nanninga, 2011). Assuming the costs of potable water to be €1.15 m^{-3} in Polderdrift[j], this could add up to €840 annually.

Since a few years, the costs for cleaning the greywater pipelines and the septic tank are increased. Twice a year a sewage cleaning company charges approximately €220 as a call-out fee plus €200 per hour (Coopmans & Van Ruijven, 2020).

The maintenance costs for Polderdrift mainly consists of the replacement of waste water distribution pumps and research related to the leakage from the filter bed. The replacement of the pumps in 2012 costed €10,000 to €12,000 (Coopmans & Van Ruijven, 2020; Van Betuw, 2005). The research activities costed €4,225 (Nanninga, 2011). The costs for the system reconstructions in 2011 are not found.

In Polderdrift, housing corporation Portaal is responsible for the financial settlement of the O&M. Nevertheless, each household has to pay €12 per month to Portaal, as a form of financial compensation. Per households this is €144 annually. However, in most years a large share of the amount is refunded by Portaal. Over 2019, 50% to 75% of the total amount was received back by the residents (Coopmans & Van Ruijven, 2020).

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[i] The calculations are based on the expected energy requirements described in subsection 4.2.3 and the multiplier of €0.22 · kWh-1 electricity, which is the Dutch price for electrical energy in 2020 (Pricewise, n.d.).

[j] €1,15 was the 2015-price of 1 m³ for the average household that was supplied by water company Vitens (Geudens, 2016).

The annual operational costs in EVA-Lanxmeer consist of the expenditures for helophyte mowing and weeding, the maintenance of the pumps and the phone bill for a phone-based feedback system. These costs items added up to €18,512 for the year 2010. Additionally, the electricity costs for the VSSF-CW systems was €1,500 in the same year. Furthermore, several component renewals took place in 2010. The expenditures of these components were approximately €18,670. The longevity of these components are expected to range from 15 to 30 years (Nanninga, 2011).

The operational costs in Drielanden are less well known. According to Nanninga (2011), the septic tank is annually emptied for €200 to €250. Furthermore, the costs for the disposal of the mowing and weeding wastes is €26 per tonne. Several tonnes of green waste have been disposed of each year. Similar to EVA-Lanxmeer, the operational costs are settled by the municipality (Gemeente Groningen, 2016).

4.5 Sociocultural dimension

The key findings of the assessment of the VSSF-CW technology in the sociocultural dimension are presented in Table 4-XII. The results for the two included assessment aspects are discussed in detail in the following two subsections.

Table 4-XII. Overview of the key findings for the product specifications and actual performance of the VSSF-CW technology in the sociocultural dimension.

Aspect	Product specifications	Actual performance (All traditional VSSF-CW)
Community involvement	Possible to involve in O&M activities.	Involvement in daily O&M activities.
		Residents were involved during design and planning phase of the water system.
	Provides opportunities for education and recreation.	Residents organize guided tours concerning the water system.
Acceptance	No increased nuisance from mosquitos and odor.	No mosquito nuisance, little odor nuisance.
	Only potential health risks if effluent is exposed to human during reuse.	No unfavorable impacts on public health; Polderdrift: fear concerning the spread of SARS-CoV-2 virus in the reuse system.
	Possible coloration of effluent due to humic acids.	
		Technology is well perceived by local community.

4.5.1 Community involvement

Product specifications

The VSSF-CW is regarded as a technology with modest complexity in its components. Therefore, high level knowledge and skill are not essential for the everyday operation of the systems. Hence, it is feasible for the local community to play a role in the operation of the VSSF-CW (Hoorn, 2017). The weekly O&M activities of the VSSF-CW are mainly the monitoring of the system components, and cleaning and weed removal when required (See Table 4-XI). These activities may be done by everyone with a basic understanding of the system (Hoorn, 2017). Besides, it is probably more suitable if actors that live nearby performs these activities because of the frequency. Van Oirschot (2020) agrees on that the frequent O&M activities are relatively simple and the local community is able to perform these. However, he mentions that it is necessary that the activities actually happen. If not, overdue maintenance can lead to technical errors and the treatment performance of the VSSF-CW gets negatively affected.

Furthermore, (Moinier, 2013) discusses the educational and recreational value of constructed wetlands in urban areas for both children and adults. The local community can be involved by receiving education from system experts, as well as being the local educator themselves. The recreational value is mainly created by the green space in the urban area. By placing facilities as park benches and street lights near the vegetated part of the system, the recreational value of the constructed wetland can be improved (Moinier, 2013). Especially the local community takes advantage from the recreational value, since other parties are not likely to visit constructed wetlands for recreational activities. Both recreation and education raise the awareness of the local people concerning their waste water treatment system. Raising awareness among the end-users seems to modestly prevent system failures, due to conscious behavior related to the domestic waste water and higher acceptance among the local population (Hoorn, 2017; Moinier, 2013).

Actual performance

Although it is not mentioned in the product specifications, the intended end-user can be involved during the design and planning stage of the VSSF-CW system. During the entire implementation of the technology in Drielanden, the project team closely communicated with the end-users. The end-users were informed via information meetings, informational handouts and a website. Besides, in order to collect the desires and thoughts of the end-user group, a part of the end-users formed a group of representatives and two questionnaires were performed (Gemeente Groningen, 2016). Gemeente Groningen (2016) concluded that the degree of involvement of the end-users contributed to the acceptance of the waste water treatment system. Leading from the experiences in Drielanden it is recommended to actively involve the end-user in the implementation projects as early as possible.

In Polderdrift, the residents had their vote in the architecture and planning of the neighborhood. The implementation of a VSSF-CW system was proposed by the residents (Coopmans & Van Ruijven, 2020). Partly because of this early involvement, the participation of the local community were well established during the first years. However, their motivation declined over time. It is assumed that this decline is caused by the decreasing share of first residents in the neighborhood. Compared to the first residents of Polderdrift, the later generations were less connected to the ecological lifestyle and the water treatment system (Coopmans & Van Ruijven, 2020; Hoorn, 2017). The gradually reducing motivation to be involved is also noticeable regarding the participation in the O&M of the VSSF-CW system (Hoorn, 2017). Nowadays, Mr. Van Ruijven (one of the earliest residents) performs the weekly O&M activities alone. However, there is the 'green team' of 15 people. This team manages some of the semi-annual O&M activities. Inhabitant Mr. Coopmans experiences the activities related to the water system as a satisfactory approach to encourage the social cohesion in the neighborhood (Coopmans & Van Ruijven, 2020). Other residents appreciate the opportunity for involvement in the O&M activities as well (Mels et al., 2007).

Hegger and Van Vliet (2010) mention that in EVA-Lanxmeer the residents are aware that the behavior of themselves possibly affects the quality of living of many others via the local water system. This interdependency contributes to the social cohesion among the community. The strong social cohesion is experienced as a positive feature by the community.

Next to the contribution to the existing literature, the educational value of VSSF-CW's in Polderdrift and EVA-Lanxmeer is established in guided tours and presentation. For example, a waste water treatment company was shown the VSSF-CW system in Polderdrift (Coopmans & Van Ruijven, 2020; Woonvereniging

Polderdrift, 2019). In EVA-Lanxmeer the residents provide guided tours and presentations about their sustainable neighborhood (BEL, n.d.).

Practical performances of the recreational competence were not found in this study.

4.5.2 Acceptance

Product specifications

As a general rule, the local community is usually willing to accept and support natural based waste water treatment systems. In literature, the constructed wetlands are considered as the ‘green’ and ‘eco-friendly’ option for decentralized waste water treatment, with the right aesthetic value for generic social acceptance. Masi et al. (2018) and Stefanakis (2019) suggest that constructed wetlands contribute to the fulfillment of the modern desire for green spaces and sustainable water management system in urban context.

Only the expected and experienced nuisances and the financial costs for the public might hinder the collective and individual consent towards implementation of constructed wetlands (Capodaglio et al., 2017; Masi et al., 2018). Pessimistic expectations of constructed wetlands generally relate to mosquito nuisance, odor emissions, public health issues and color of the effluent. Often, natural wetlands provide the habitat for mosquitos. Therefore, a commonly asked question to the system installer is whether the implementation of a VSSF-CW system leads to an increase in the local mosquito population. However, mosquitos prefer stagnant surface water to live and breed. Additionally, since the waste water is in a closed system or in the subsurface almost the entire time of the treatment process, the mosquitos do not benefit from the presence of a VSSF-CW (Ecofyt, n.d.-b; Hoffmann et al., 2011; Rietland bvba, n.d.-d; Wetlantec Nederland B.V., n.d.).

Additionally, the Dutch system installers assert on their websites that the concern for odor nuisance near VSSF-CW systems is irrelevant (Ecofyt, n.d.-b; Wetlantec Nederland B.V., n.d.). Odors may result from the ponding of waste water on top of the filter bed. However, if the VSSF-CW system is well designed, constructed and operated, the waste water is in a closed system or in the subsurface almost the entire time of the treatment process (Hoffmann et al., 2011; SSWM, n.d.-b; Van Oirschot, 2020).

Similar to the mosquito and odor nuisances, the risks to public health are also limited by the presence of the waste water in the subsurface. Since the water is almost the entire time during process within a closed system or in the subsurface, the only exposure risk is the effluent if it is reused. As found for the removal efficiencies, a certain proportion of pathogens can still be present in the effluent, especially when black water is also treated by the VSSF-CW (subsection 4.2.1). In order to minimalize the health risks, tertiary treatment steps should be added to the system when effluent reuse activities with high exposure to humans are considered (Van Oirschot, 2020).

The concern for the color of the effluent is only relevant if the water is reused for household usage. Due to humic acids in the effluent, the water colors might be yellowish or brownish (Van Oirschot, 2020). The coloration possibly reduces the acceptance of people to reuse the effluent. In general, people expect and desire clear water for household activities. If the effluent is reused for toilet flushing, it is recommended to choose for toilet bowls with colored porcelain instead of extensive color treatment. An additional drawback of the coloration is that the effluent can be treated less efficiently when UV radiation or chlorination are used as tertiary treatment steps (Hoffmann et al., 2011). The forced aeration VSSF-CW system configuration is proposed as a solution to this problem. According to Van Oirschot (2020), the Phytoair system[k] produces a crystal clear effluent.

Actual performance

In all three practical cases the VSSF-CW system was perceived as a desirable technology for waste water treatment. Especially the environmental and social values of the system contribute to the acceptance among the end-users. The green space in the urban context, the benefits to the local nature (e.g. birds breeding sites, improved surface water quality and emergence of plant species) and the quietness of the area are considered as desirable improvements to the local environment (Nanninga, 2011; Van der Eijk et al., 2018). Since the filter bed is continuously supplied with water, the VSSF-CW kept these contributions to the resident comfort during warm and dry summer periods as well (Coopmans & Van Ruijven, 2020). Although, the above ground helophyte parts perish or are mowed during the colder seasons. Hence, the visual aesthetic value is reduced during winter.

The social value is mainly induced by the involvement of the community and the shared responsibility (Hoorn, 2017; Nanninga, 2011). The case of Polderdrift exemplifies the relation between social acceptance and community involvement. As the involvement of the residents was decreased after several years of operation, the necessity of the VSSF-CW was questioned. In 2012, when reparation of the technology was required, some residents doubted the investments and affords that were needed for continuing the VSSF-CW system. Nevertheless, the system was repaired and it maintained in operation (Coopmans & Van Ruijven, 2020).

Although the VSSF-CW systems are experienced as comfortable systems for the end-user, minor changes in the behavior of the end-user is required to prevent technical errors. The main behavioral change is to prevent certain constituents to be drained during household activities. In Polderdrift and EVA-Lanxmeer the residents are provided with information booklets containing a list of substances that should not be flushed down the drains (Appendix 4). According to Coopmans and Van Ruijven (2020), following these guidelines is not experienced as troublesome for the two men. However, the men do not know how strictly their neighbors act regarding the restrictions. Nevertheless, the VSSF-CW has not shown any technical errors that could be traced back to incorrect behavior of residents concerning the flushing of the restricted substances. Similar experiences are found in EVA-Lanxmeer (Nanninga, 2011). In Drielanden the waste water distribution pumps once clogged

[k] A product of Rietland bvba.

due to the flushing of wet wipes. The residents were asked to avoid the flushing of wet wipes by the system operator. In order to accommodate the residents, the municipality gave away free sanitary waste bins (Gemeente Groningen, 2016).

In advance of the system implementation, concerns about a locally increasing mosquito population rose in EVA-Lanxmeer and Drielanden. In Drielanden it was considered as a threat to the public health, as it was expected to reintroduce malaria in the region (Nanninga, 2011). However, over the 24 years of operation no cases of malaria infection were related to the VSSF-CW. Furthermore, questioned residents in all three practical cases do not experience an increased nuisance from mosquitos in their neighborhood (Coopmans & Van Ruijven, 2020; Nanninga, 2011).

Also for other public health risks no actual cases have been recorded in the three VSSF-CW projects. In Polderdrift, a legionella risk assessment was performed in 2003. The reason for that were the legionella infections occurring in the Leidsche Rijn neighborhood in Utrecht (NL). There, the infections were allocated to the circular water system including household water reuse (Oesterholt et al., 2003). The water system of Polderdrift was precautionary checked on legionella risks by C-mark BV. C-mark BV concluded that there were no increased risks of legionella infection due to the decentralized waste water treatment and reuse system (Van Betuw, 2005). Furthermore, the VSSF-CW systems in EVA-Lanxmeer and Drielanden are fenced to discourage people to enter the filter bed surface.

During the field visit in Polderdrift, the VSSF-CW system was temporarily shut down due to the concerns for the spread of the SARS-CoV-2 virus. Some residents of Polderdrift fear for the waste water reuse loop to contribute to faster spread of the virus amongst the neighborhood (Coopmans & Van Ruijven, 2020). However, no proof for spread and virus infection via sewage system is found yet (RIVM, n.d.).

Experiences of odor nuisance are recorded in all three practical cases over the period of functioning. Bad smells appear when the waste water is in contact with the open air for too long. In the practical cases these situations occurred when the filter bed was (partly) clogged. Puddles of waste water emerged on the filter bed surface, which created the unpleasant smells (Nanninga, 2011). Though, the smell is experienced differently among the local communities. For instance, the odor nuisance is depending on the wind direction and time of waste water pumping in Polderdrift (Coopmans & Van Ruijven, 2020; Hoorn, 2017; Mels et al., 2007). Moreover, in Drielanden some residents experienced the odor as a nuisance, while others could not discern it from odors originating from local agricultural activities. The residents of Drielanden accepted the odors as a part of their living environment (Nanninga, 2011).

5. DESAH system

5.1 Description of the technology

5.1.1 General system set-up

The DESAH system is a succession of waste water treatment technologies, targeting to treat all domestic waste water. The separation of domestic black and grey waste water is required for the implementation of the DESAH system. The black water is treated in three reactors. First, the black water is treated in an Upflow Anaerobic Sludge Blanket (UASB) reactor. For optimal treatment in the UASB reactor, a well concentrated stream of black water is required. Therefore, the black water is collected and transported via vacuum toilets and vacuum sewers with a minimized flushing water requirement. Additionally, an organic waste grinder (commonly installed in the kitchen) is connected to the vacuum sewers. Hence, small-sized organic waste is added to the black water stream prior to the treatment in the UASB reactor. After the treatment in the UASB reactor, the black water[I] is treated according to the Oxygen-limited Autotrophic Nitrification/Denitrification (OLAND) process in a rotating biological contactor (RBC). Subsequently, the water is treated in the struvite reactor. The effluent of the struvite reactor then mixes with the generated grey water. Ultimately, the mixed waste water stream is treated in a two-stage adsorption/bio-oxidation (AB) process (Figure 5.1).

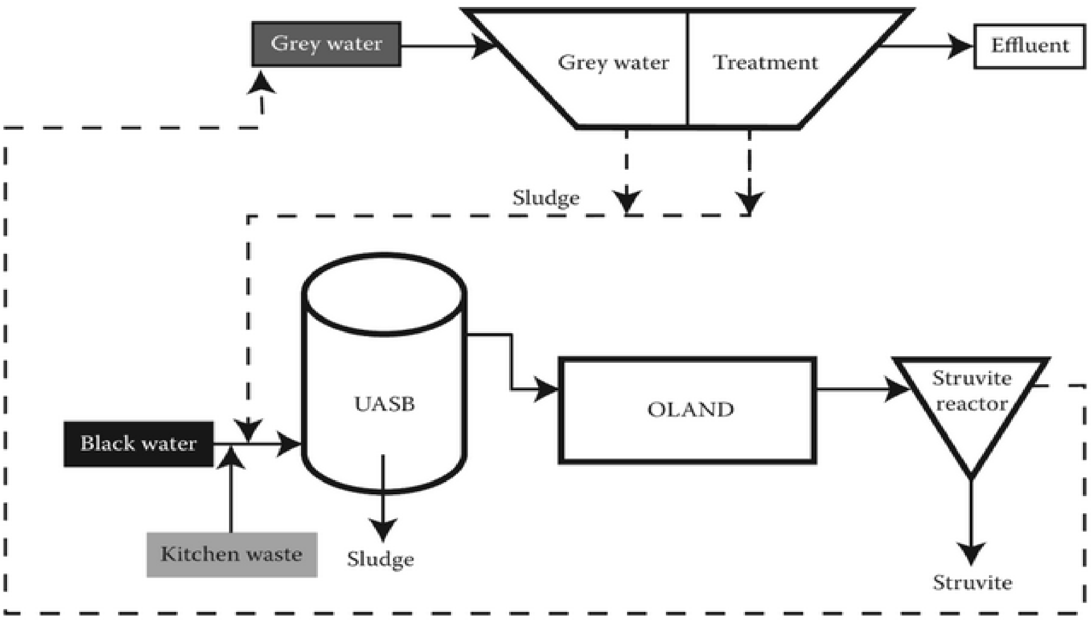

Figure 5.1. Schematic representation of the DESAH system. Adapted from Van Eekert & Zeeman (2017).

After the treatment processes, the waste water still has a relatively high temperature of 20˚C to 25˚C (DESAH BV, n.d.-c). The high temperature caused by the inclusion of shower and bathing water in the grey water stream and by the black water treatment in the heated UASB reactor. In order to recover the thermal energy from the final effluent, a compact heat exchanger is installed as the last part of the DESAH system.

[I] Including the added small-sized organic waste.

5.1.2 Waste water treatment principles

Anaerobic digestion (UASB reactor)

High concentrations of organic matter are present in black water stream. Especially when it is mixed with little volumes of toilet flushing water and supplemented with grinded organic waste. In order to treat the organic matter, anaerobic digestion takes place in the UASB reactor as the first stage of the black water treatment (STOWA, 2014). The UASB reactor is a tank where the waste water enters at the bottom and flows upward. Just above the inlet, the upward flowing water passes a suspended sludge blanket (Figure 5.2). The sludge blanket consists of small agglomerations of microorganisms. The agglomerations are typically 1 to 3 mm in diameter, so that the weight is sufficiently large to prevent being washed out by the upward flowing water. The sludge blanket filters other suspended solids from the upward flowing waste water. The microorganisms digest the organic matter particles, and excrete a gas mixture that mainly comprises of methane and carbon dioxide. The gas mixture (biogas) is released at the top of the tank (Tilley et al., 2014). The efficiency of the digestion process is dependent on the temperature in the UASB reactor. Optimally, the temperature is 30˚C to 35˚C (STOWA, 2014). The sludge blanket stays suspended as the result of the rising biogas and the upwards water flow. Normally, a flow velocity of about 0.7 to 1 m h^{-1} is required to maintain the suspension (Tilley et al., 2014).

Due to the digestion of the organic matter in the black water, the biological and chemical oxygen demand (BOD and COD) are well decreased at the outlet of the UASB reactor. Additionally, organic nitrogen is converted to dissolved ammonium (NH_4^+). Furthermore, a part of the phosphate bindings precipitate with metal ions in the UASB reactor (STOWA, 2014).

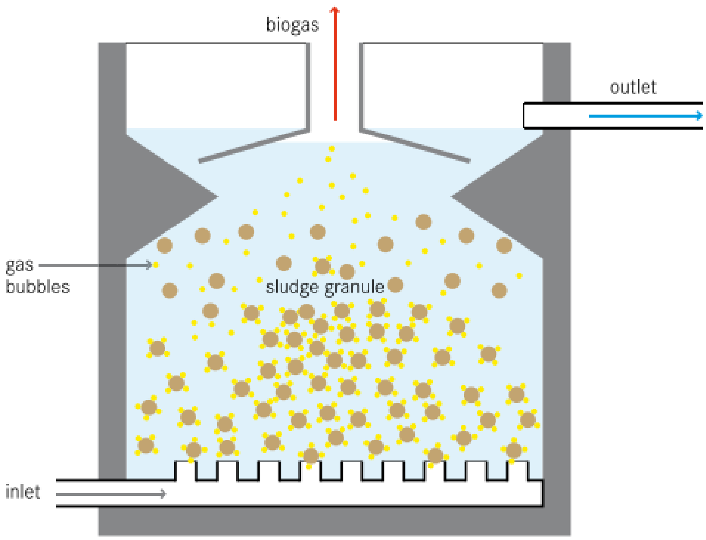

Figure 5.2. Schematic representation of a UASB reactor. Adapted from Tilley, Ulrich, Lüthi et al. (2014).

Biological nutrient removal (OLAND RBC)

Waste water with a high NH_4^+ concentration flows from the outlet of the UASB reactor to the OLAND RBC (STOWA, 2014). In the OLAND RBC a part of the NH_4^+ is converted to NO_2^- by aerobic ammonium oxidizing bacteria (AerAOB) with oxygen as the electron acceptor (nitrification). Subsequently, the produced NO_2^- is used by anoxic ammonium oxidizing bacteria (AnAOB) as the electron acceptor to oxidize remaining NH_4^+ ions. As a byproduct from the latter conversion, N_2 gas is formed which is able to volatilize (Windey et al., 2005). Overall, both the ammonium concentration and the total nitrogen load are reduced during the process in the OLAND RBC (STOWA & Rioned, n.d.-e).

The OLAND RBC comprises of a series of vertical oriented discs that slowly rotate around their horizontal axes (Figure 5.3). On the entire surface of the discs a biofilm with the two bacteria groups is formed. The water level in the RBC is located so that only the lower part of each discs is inundated. By rotating the discs, the aerobic and anoxic conditions are alternated. So, both AerAOB and AnAOB based processes occur at the surface of the discs. With the height of the water level, the rotational speeds and the type of biofilm supporting media (discs) the ratio between the two processes can be adjusted. If the water level is relatively low (i.e. at 40 to 50% of the top of the disc height), a high reduction rate of BOD and COD occurs (Berckmoes, 2012; Cortez et al., 2008).

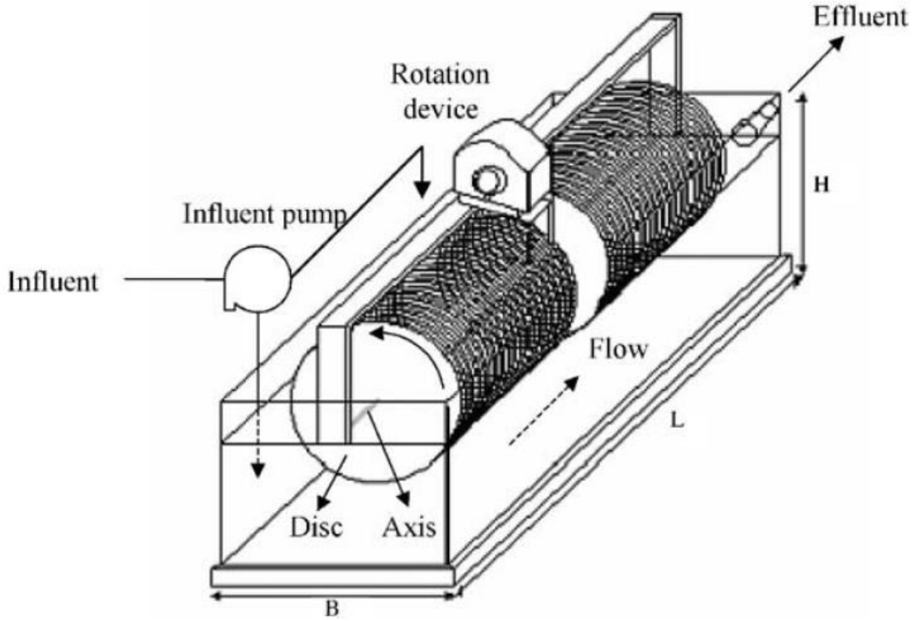

Figure 5.3. Schematic representation of an OLAND RBC. Adapted from Windey et al. (2005).

Struvite precipitation (struvite reactor)

The last stage of the black water treatment in the DESAH system is the struvite reactor. By adding magnesium salt, the remaining NH_4^+ and phosphorus in the waste water (OLAND RBC effluent) precipitate as struvite ($MgNH_4PO_4$) crystals (Van Merksteijn, 2016). The struvite crystals settle in the reactor. Subsequently, the crystals can be removed from the waste water. Figure 5.4 shows the schematic representation of a struvite reactor.

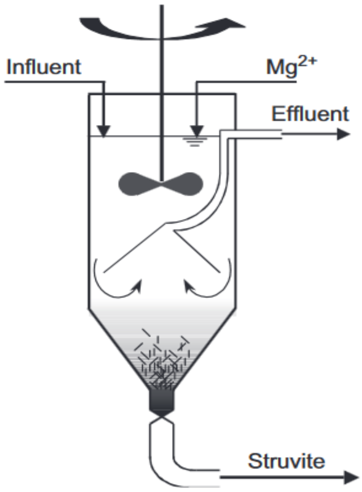

Figure 5.4. Schematic representation of a struvite reactor. Adapted from Wilsenach et al. (2007).

AB process

The grey water is transported from the households to the AB system gravity sewers. The effluent of the struvite reactor is added to the grey water stream, and this combined stream is further treated according to the two-staged aerobic AB process. First, the majority of the organic matter is removed by the adsorption to sludge flocs (bio-flocculation). The sludge product of the bio-flocculation settles in a sedimentation tank. This sludge is then transported to the UASB reactor for additional treatment. Subsequently, the waste water is subject to an activated sludge treatment under aerobic conditions. The microorganisms in the sludge blanket mineralize the remaining organic matter and oxidize NH_4^+ present (nitrification) (Van Merksteijn, 2016).

5.1.3 Technological advancements

Currently the replacement of the AB process by a membrane filtration step is being developed (Metz, 2020). In practice, the membrane filtration is combined with an antecedent aeration step. By membrane filtration particles of a certain range of fraction sizes can be physically separated from the water. The membrane filter in the DESAH system is developed to separate pharmaceuticals, hormones, antibiotics, personal care products and micro-plastics, bacteria and viruses that where not removed during the previous treatment steps (DESAH BV, n.d.-c). The residue of the filtration can possibly be recycled back to the UASB reactor. The fate of the residue is currently being researched (Metz, 2020).

5.1.4 System configurations in practical case

Initially, the technology sequence in Noorderhoek is set-up as the system described in subsection 5.1.1. However, in 2017 the A-stage (bioflocculation) of the AB-process is removed because it performed insufficiently (De Wit et al., 2018). Table 5-I presents the known operational parameters of the DESAH system in Noorderhoek.

Table 5-I. Known operational parameters for the two configurations of the DESAH system in Noorderhoek.

System component	Parameter	Unit	Noorderhoek (excluding A-stage) (De Graaf & Van Hell, 2014; Wiersma, 2012)	Noorderhoek (including A-stage) (De Wit et al., 2018)
	Connected Residents	p.e.	79	327
BW treatment	Design capacity	p.e.	1530	1530
GW treatment	Design capacity	p.e.	727	727
UASB reactor	Temperature	˚C	35	37
	Volume	m³	37	-
	Discharge	$l\ d^{-1}$	1045	3597[m]
	Retention time	d	39	-
	Upward flow velocity	$m\ d^{-1}$	0.15	-
OLAND RBC	Temperature	˚C	27.5	-
	Volume (fluid)	m³	3.5	-
	O_2 concentration	$mgO_2\ l^{-1}$	1.0	-
	pH	-	7.5	-

[m] Based on connected residents in 2016 (327) and potable water use for toilet flushing and kitchen waste transport (11 $l\ d^{-1}$ p.e.$^{-1}$).

5.2 Environmental dimension

The key findings of the assessment of the DESAH system in the environmental dimension are presented in Table 5-II. The results for the five included assessment aspects are discussed in detail in the following five subsections.

Table 5-II. Overview of the key findings for the product specifications and actual performance of the DESAH system in the environmental dimension.

Aspect	Product specifications	Actual performance
Water treatment efficiency	Effluent quality meets IBA class IIIb standards.	Only the TP concentration in effluent substantially exceeds the legal standards during 2012-2014.
		After 2014, TP removal is well improved by adding more magnesium salts to the struvite reactor.
	High effluent quality, especially if membrane filtration is included.	
		Substantial contribution to the removal of a range of pharmaceuticals.
Local water balance	Saves 23% to 27% of the total potable water consumption due to vacuum toilet.	Saves 4% to 30% compared to the Dutch average potable water consumption.
		In-home dislocation of waste water results in a higher volume of black water than expected + a lower volume of grey water.
	Effluent quality is sufficient for discharge to local surface water	Effluent is discharged to local surface water.
	Toilet flushing, showering, laundry, garden irrigation, outside cleaning or thermal energy carrier are feasible reuse applications for the effluent.	
Nutrient recovery	Struvite production of 9.7 to 12.0 gram per day.	K-struvite is produced due to an ammonium deficit; no available data on the production rate is available.
	The produced struvite is a beneficial agricultural fertilizer.	No information on the application of the produced K-struvite is available.
Energy balance	Require electrical and thermal energy.	Heat and biogas recovery play a major role for the positive energy balance.
	Heat can be recovered from the waste water.	
	Biogas can be recover, as a byproduct of the UASB reactor.	
		Without technical errors, the net energy balance is positive (energy producing).
Spatial requirements	Vacuum system and treatment components require most space.	Facility building requires up to 3.5 times less surface area compared to a WWTP.
	Treatment facilities can be placed in various locations.	

5.2.1 Water treatment efficiency

Product specifications

According to Mr. Metz, the technical director of the DESAH company, the final effluent of the DESAH treatment system is of high quality and conveniently meets the Dutch waste water discharge quality standards for small WTTPs (see Table 2-I). Theoretically, the effluent of the DESAH system including the membrane filtration technology should have the quality values that are shown in Table 5-III. More specifically, Metz (2020) stated that 80% to 90% of the COD in the black water stream is removed in the UASB reactor, 70% to 80% of the NH_4^+ is removed in the OLAND RBC, and 80% of the TP is removed in the struvite reactor. Furthermore, 80% to 90% of the COD of the combined stream of grey water and struvite reactor effluent is removed by the membrane filtration including the aeration antecedent step.

Table 5-III. Effluent quality of the DESAH system according to DESAH BV (n.d.-c).

Parameter	Unit	Effluent DESAH system
COD	mg l^{-1}	Not detectable (<< 10)
TN	mg l^{-1}	3.6
NH_4^+	mg l^{-1}	3.4
NO_3^-	mg l^{-1}	0.2
TP	mg l^{-1}	0.52
PO_4^{3-}	mg l^{-1}	0.47
Hardness	mmol l^{-1}	< 0.895

Actual performance

Due to the vacuum toilet, the black waste water stream is very concentrated. Sequential, the concentrations of COD, TN, TP and a range of pharmaceutical are high in the influent of the DESAH system. According to Wiersma & Elzinga (2014), the concentrations metformin and Hydrochlorothiazide (see Table 5-V) are 6 and 300 times higher compared to the influent of the WWTP in Deventer (The Netherlands). However, the composition of the end-users in Noorderhoek during the monitoring period partly explains the high pharmaceutical concentrations. The DESAH system treated the waste water produced by mainly elderly households, and more than 40% of the end-users were residents of a nursing house.

Wiersma & Elzinga (2014) performed a long-term monitoring study on the treatment performance of the DESAH system in Noorderhoek in 2014. The removal efficiencies of all DESAH system components in Noorderhoek are presented in Table 5-IV. As expected from the description of the treatment processes in subsection 5.1.2, the COD value is well reduced in the UASB. Also, the concentration of NH_4^+ has increases, which indicates the conversion of organic material. The higher concentration of NH_4^+ is important for the potentials of nitrification and nitrogen removal in the OLAND process. From the monitoring data the concentration of NH_4^+ and TN are reduced properly. However, the COD value increases in the OLAND RBC. This can be explained by the generation of biofilm and sludge in the RBC. As expected, the TP and PO_4^{3-} concentrations were considerably reduced in the struvite reactor. Also, the COD value has decreased in the reactor. The grey water treatment was the full AB-process during the monitoring period. This treatment step appears to be important for the removal of COD, TN, NH_4^+ and TP from the combined stream of domestic grey water and the struvite reactor effluent. The high PO_4^{3-}/TP ratio shows that most phosphorus compounds are converted into PO_4^{3-}. Furthermore, the AB-process also efficiently reduced the concentrations of a range of pharmaceuticals in the grey water. The removal of pharmaceutical compounds in the AB-process is shown in Table 5-VI.

Regarding the quality parameters included in the Dutch legal standards, the 2014-effluent of the DESAH system meets the criteria for COD, TN and NH_4^+. The TP concentration however is a factor 5 to 8 too high. The treatment performance of the system configuration without the A-stage treatment shows considerably improved TP removal. The TP concentration in the final effluent approaches the legal standards for small WTTPs, but is still slightly too high. The improvement in the TP removal efficiency is mainly the result of increasing the magnesium salt supplementation in the struvite reactor (Wiersma & Elzinga, 2014). The data from the configuration without the A-stage treatment is limited and lacks the removal efficiencies of the specific system components. Hence, the effects of excluding the A-stage does not become clear from these data.

Moreover, no information concerning the concentration of microbial pathogens is available.

Table 5-IV. Effluent quality and removal efficiencies of the DESAH system and its components.

System component	Parameter	Initial set-up Noorderhoek (Wiersma & Elzinga, 2014)	Current set-up Noorderhoek (De Wit et al., 2018)
		Effluent quality in mg l^{-1} (% removal)	
UASB	COD	720 (92)	
	TN	960 (4)	
	NH_4^+	820 (-28)	
	TP	86 (22)	
	PO_4^{3-}	76 (5)	
OLAND RBC	COD	991 (-38)	
	TN	285 (70)	
	NH_4^+	29 (96)	
	NO_3^-	181	
	NO_2^-	12	
	TP	83 (3)	
	PO_4^{3-}	65 (13)	
	K^+	420	
	Mg^{2+}	59	
Struvite reactor	COD	254 (74)	
	TN	276 (3)	
	NH_4^+	22 (24)	
	NO_3^-	206 (-14)	
	NO_2^-	8 (33)	
	TP	20 (76)	
	PO_4^{3-}	9 (86)	

Continued on next page

Table 5-IV continued from previous page

Total BW sequence	COD	254 (97)	
	TN	276 (72)	
	NH_4^+	22 (97)	
	TP	20(82)	
	PO_4^{3-}	9 (89)	
Grey water treatment	COD	57 (89)	54.4
	TN	6.7 (66)	6.1
	NH_4^+	0.8 (65)	
	NO_3^-	2.3	
	NO_2^-	0.1	
	TP	13.5 (21)	2.6
	PO_4^{3-}	12.6 (-21)	
Entire DESAH system	COD	57 (97)	54.4 (96)
	TN	6.7 (96)	6.1(96)
	NH_4^+	0.8 (99)	
	NO_3^-	2.3	
	NO_2^-	0.1	
	TP	13.5 (55)	2.6 (85)
	PO_4^{3-}	12.6 (37)	

Table 5-V. Removal of pharmaceutical compound in the black water sequence. Table adapted from Wiersma & Elzinga (2014)

Substance	Influent (µg l^{-1})	Effluent (µg l^{-1})	Removal (%)
Paracetamol[n]	2730.1	0.30	99.7
Ibuprofen	85.6	2.72	96.8
Diclofenac[m]	4.7	3.93	16.2
Naproxen	362.0	0.37	99.9
Metformin	4286.5	4.64	99.9
Hydrochlorothiazide	493.1	23.56	95.2
Metoprolol	357.0	116.01	67.5
Oxazepam	24.7	3.21	87.0

Table-VI. Removal of pharmaceutical compound in the AB-process. Table adapted from Wiersma & Elzinga (2014)

Substance	Influent (µg l^{-1})	Effluent (µg l^{-1})	Removal (%)
Galaxolide	12.45	4.3	65.4
Octinoxate	13.44	0.42	96.9
Methylparaben	4.39	0.15	96.7
Ethylparaben	1.55	0.00	99.9
Propylparaben	2.07	0.03	98.5
Buthylparaben	0.32	0.00	99.2
Triclosan	20.51	5.80	71.7
Triclocarban	4.10	0.86	79.0
Benalkonium chloride	10.04	0.46	95.5
Caffeine	1174.52	216.09	81.6

[n] Effluent measured after the OLAND reactor.

5.2.2 Local water balance

Product specifications

The DESAH system affects both the potable water use and the potential for the fresh water availability at local scale. The inclusion of vacuum toilets is the main reason for the savings of potable water used in-home. A typical vacuum toilet uses 1 liter potable water per flush. Also modern vacuum toilets exist that only use 0.5 to 0.8 liter per flush. Conventional toilets consume 6 to 9 liter per flush (Kujawa-Roeleveld, 2005), resulting in a daily consumption of 34.6 l d^{-1} $capita^{-1}$ (Geudens & Grootveld, 2017). Theoretically, the replacement of a conventional toilet with a vacuum toilet could save 83% to 94% of the potable water consumption for toilet flushes. On a daily basis 28.8 to 32.7 liter water per person can be saved.

On the contrary, a kitchen grinder requires water for the transport of the grinded kitchen waste. Kujawa-Roeleveld (2005) estimates a water consumption of 0.5 l d^{-1} $capita^{-1}$ to transport the small-sized kitchen waste. Compared to the potential savings from the vacuum toilet, the added consumption is only marginal. Based on the total daily consumption of 119.2 l $capita^{-1}$ (Geudens & Grootveld, 2017), the DESAH system potentially saves 23% to 27% of the water consumed in households.

If the potable water consumption is reduced by 27% and all other consumed water turns into waste water, the DESAH system treats about 86.6 l d^{-1} $capita^{-1}$ (Figure 5.5). Hence, that amount of treatment effluent comes available on neighborhood level.

If the membrane filtration step is included, the final effluent of the DESAH system should be of sufficient quality for discharge to local surface water bodies. Besides, the effluent has the potential for reuse application on neighborhood level (DESAH BV, n.d.-c; Metz, 2020). Kujawa-Roeleveld (2005) discusses the reuse of the effluent for agricultural irrigation. However, the effluent quality must be suitable for this application. The accumulation of salts and trace elements in the crops and soil should be avoided because of the environmental damage. Also the content of microbial pathogens in the water is important if irrigation of edible crops is considered (WHO, 2016). Moreover, the treated water can be transported back to the households for the applications of toilet flushing, showering, laundry, garden irrigation or outside cleaning (e.g. car washing or high pressure cleaning of walls). The advantage of the DESAH effluent for household reuse is that it has a considerably low hardness in theory (see Table 5-III). Water with a low hardness value is more suitable as a thermal energy carrier through heating elements and soap-based washing purposes (WHO, 2011)

Actual performance

Figure 5.5 shows the daily water consumption and waste water generation in Noorderhoek. As foreseen in the product specifications, the potable water use was considerably lower in Noorderhoek in 2014 than in the average Dutch household. The actual potable water savings are 30% on average (Wiersma & Elzinga, 2014), which is even more than the product specifications describe. This better performance might be the result of a higher awareness among the residents concerning the potable water consumption (Metz, 2020).

In 2014, the total waste water generation in Noorderhoek was 84 l d^{-1} p.e.$^{-1}$ on average (Wiersma & Elzinga, 2014). This is slightly less than expected from the product specifications. The main differences can be found in the lower grey water generation rate and the higher black water generation rate in Noorderhoek. These differences can be explained by that Dutch residents sometimes flush waste water that is considered to be a grey water through the toilet (e.g. waste water from cleaning and mopping). Hence, the grey water stream is smaller and the black water stream is larger than expected (Wiersma & Elzinga, 2014). Furthermore, the frequency of toilet flushing might contribute to the higher black water generation. Dutch residents in the age group of 65 years and older use approximately 30% more water for toilet flushing (Van Thiel, 2017).

Compared to 2014, the potable water consumption was 36% higher and grey water generation was 47% higher than in 2017. De Wit et al. (2018) suggests that this might be caused by the composition of the end-user group. Since 2014 the polluter equivalent has increased from 79 to 327. The newly connected households mainly consisted of families with children. Compared to Dutch residents of 65 years and older, the younger age groups use remarkably more water for showering and bathing and less for toilet flushing (Van Thiel, 2017).

Furthermore, the effluent of the DESAH system in Noorderhoek is not used for reuse applications. The effluent is discharged to a nearby surface water body in the neighborhood (De Graaf & Van Hell, 2014).

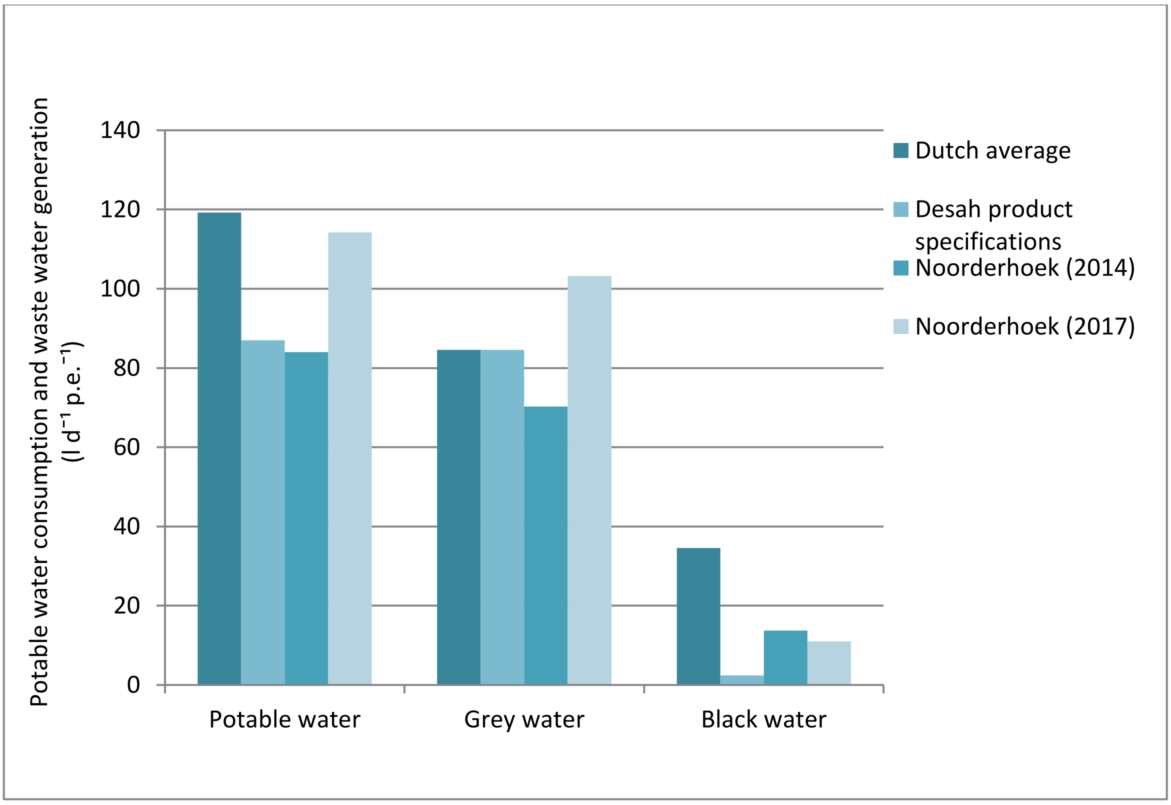

Figure 5.5. Average daily water consumption and waste water generation. Adapted from De Wit et al. (2018) and Wiersma & Elzinga (2014)

5.2.3 Nutrients recovery

Product specifications

One of the objectives of the DESAH system is to contribute to local circularity of resources (Hermans, 2014). A potential valuable byproduct of the system is struvite ($MgNH_4PO_4$) crystal. Struvite crystals can be used as a slow phosphorus releasing fertilizer for agricultural soils. Advantages of the relatively slow P-release by struvite (granulate) are that the P availability for the crops is spread over a longer period and the leaching of the nutrient to surface water bodies is limited (Everaert et al., 2018; Talboys et al., 2016). Therefore, the DESAH system is designed to recover the settled struvite crystals from the struvite precipitation can be obtained from the reactor.

Le Corre et al. (2009) found in literature that 60% to 70% of the total phosphorus could be removed by struvite precipitation easily. They even found cases with removal rates of higher than 90% via struvite precipitation from waste water. The limited factors for the struvite precipitation are the available amounts of phosphorus, ammonium and magnesium salts. Furthermore, a pH of more than 6.5 is favorable for the struvite precipitation process. DESAH BV (n.d.-c) states that from an installation treating 5 m³ of black water per day approximately 4.4 kg struvite can be recovered. Converted to 1 p.e. that would lead to 9.7 to 12.0 gram per day for the DESAH system.

Actual performance

In Noorderhoek a different type of struvite crystals was gained as explained above. Table 5-IV shows that the OLAND RBC effluent a limited NH^+ concentration and abundant potassium ions (K^+) available. Together with an increased pH value (9-10) from the addition of magnesium salts, available orthophosphate precipitated with K^+ as potassium struvite ($MgKPO_4$ $6H_2O$) crystals (Wiersma & Elzinga, 2014). Nonetheless, Thomsen (n.d.) indicated that K-struvite has similar properties as an agricultural fertilizers as ammonium-based struvite. Hence, this byproduct is still valuable.

No data concerning the recovered amount of K-struvite in Noorderhoek is available. Neither the amounts of generated and recovered ammonium-based struvite during periods of low (> 9) pH values is available. Furthermore, no information indicates the actual reuse of the obtained struvite.

5.2.4 Energy balance

Product specifications

Multiple components of the DESAH system require energy in order to operate. The vacuum system, the kitchen grinder, the waste water distribution pumps, the OLAND RBC, the struvite reactor, the grey water treatment components and heat exchangers all consume electricity. Besides, the UASB reactor and the AB-process require thermal energy (Arias et al. 2020).

On the contrary, the DESAH system is designed to recover energy from the waste water and the treatment processes. The heat from the waste water stream and the biogas released from the anaerobic digestion are targeted to recover for local application. The heat in the grey waste water stream is mainly originating from the warm shower and bathing. Additional, the black water stream contains heat as well, since the UASB reactor operates at approximately 35°C internally. The thermal energy from the water stream is extracted in the heat exchanger at the end of the DESAH system. The energy carried by the biogas can be converted into thermal energy via combustion. The recovered energy can be for example applied to supply the heat-requiring system components or heat local houses and buildings (Metz, 2020).

Actual performance

During 2014 and 2017, the energy consumption and production were monitored for the DESAH system in Noorderhoek. Also, the 2017-data were extrapolated for the situation with the system operating on full design capacity (i.e. 1530 p.e.). The energy related performance of the system is shown in Table 5-VII.

Overall, the system had a negative net total of the energy balance. This means that the recovered energy did not exceed the energy consumption of the system. In 2014 and 2017, the net totals were -19.2 and -26.4 kWh p.e.$^{-1}$ year^{-1}, respectively. The DESAH system required slightly less than the average Dutch WWTP (2006-2015), which consumed 26.3 to 30.6 kWh p.e.$^{-1}$ year^{-1} (see Table 4-VI).

It is projected that the proportional energy consumption by the waste water treatment components and the operation of the heat exchanger will decrease if more end-users will be connected to the system. On the contrary, less thermal energy per p.e. will be recovered by the heat exchanger. This is mainly caused by the performance of the heat exchanger. The capacity of the heat exchanger is not designed for the recovery of heat in the 1530 p.e. situation. Nevertheless, an improved net energy balance can be expected if more residents will connect to the DESAH system in Noorderhoek (De Wit et al., 2018).

Furthermore, the biogas production could entirely cover the heat demand for the waste water treatment processes of the 2017-DESAH system in Noorderhoek.

5.3.5 Spatial requirements

Product specifications

The components of the DESAH system are mainly located outside of the households. Only the vacuum toilets, the kitchen grinder and the waste water transport pipes are located inside the homes. The treatment components, the vacuum pump, the waste water collection wells and additional byproduct collection facilities cover the majority of the total spatial requirements. As indication, the dimensions of the treatment components for a hypothetical DESAH system associated with an office building for 1000 employees are presented in Table 5-VIII.

Table 5-VII. Energy balance of the DESAH system in 2014 and 2017. The last column shows the extrapolated data for the full capacity (1530 p.e.) of the system. The data represent the primary energy equivalent° of the consumption and production in kWh $p.e.^{-1}$ $year^{-1}$. Table based on data from De Wit (2018) and Lindeboom & De Wit (2014).

Component energy balance	Noorderhoek 2014 (79 p.e.)	Noorderhoek 2017 (327 p.e.)	Noorderhoek full capacity (1530 p.e.)
Consumption			
Waste water and kitchen waste transport (electricity)	-70.5	-51.0	-51.0
Kitchen grinder (electricity)	-15.0	-15.0	-15.0
BW treatment (Heat)	-235.6	-126.5	-126.5
GW treatment (Heat)	-41.7	0	0
Treatment components (electricity)	-160.75	-152	-72.25
Heat exchanger (electricity)	-105.8	-103	-67.3
Energy recovery			
Biogas (heat)	133.4	149.9	149.9
Heat recovery (heat exchanger)	476.8	271.2	176.7
Net total	**-19.2**	**-26.4**	**-5.5**

The outside components can be positioned in a relatively compact way (Metz, 2020). In general, a facility building is realized to harbor the components. Additional value can be created by realizing a green roof or the placement of solar panels. Besides of harboring the treatment components, the facility building can also be extended and used for other applications that fit in the urban environment. Furthermore, aesthetic value can be created by the architecture of the building.

Instead of upgrading the facility building, the treatment components can be located in other places than a facility building at street level. For instance, the treatment components are located on a floating vessel with a fixed location in a pilot set-up in Amsterdam (NL) (DESAH BV, n.d.-a). The reason for that choice is based on the high land price in Amsterdam (Metz, 2020). Another example is an underground located UASB reactor in a business district in The Hague (NL). Since the space is very limited in this district, a UASB reactor is placed in an underground parking lot (DESAH BV, n.d.-b).

Table 5-VIII. Dimension of a hypothetical DESAH system for an office building (1000 employees). Data adapted from DESAH BV (n.d.-c).

System component	Area size (m^2)	Height (m)
UASB reactor	7.1	6
OLAND RBC	8	1.5
Struvite reactor	4	3
Grey water treatment (aeration, membrane filtration & heat exchanger)	5	1.5 - 2

Actual performance

The outside components of the DESAH system in Noorderhoek are located in a compact facility building in center of the connected households (Figure 3.4). The building covers an area of 150 to 200 m². The waste water treatment components are located inside the building and the vacuum pump and raw grey water well are

° Data found on the electricity consumption is converted to primary energy consumption by a factor 2.5, based on a conversion efficiency of 40%.

located under the surface level near the building (Figure 5.6). While in 2014 79 residents were connected, DESAH system in Noorderhoek is designed for 1530 p.e.. According to Blom (2014), the current facility building does not have to be adjusted if the number of connected residents grows up to the treatment capacity. Hence, the spatial requirement of the system components outside the households potentially is 0.1 to 0.13 m² per p.e. Compared to the specific spatial requirement of the WWTP in Deventer (NL) of 0.35 m² p.e.$^{-1}$ [p] (Blom, 2014), the spatial requirement of the DESAH system could be 3.5 times smaller.

Qualitywise, the facility building is adjusted to the architecture of the homes in the Noorderhoek neighborhood (Figure 5.6). Compared to a communal WWTP, the appaerance is assumed to be less industrial (Blom, 2014).

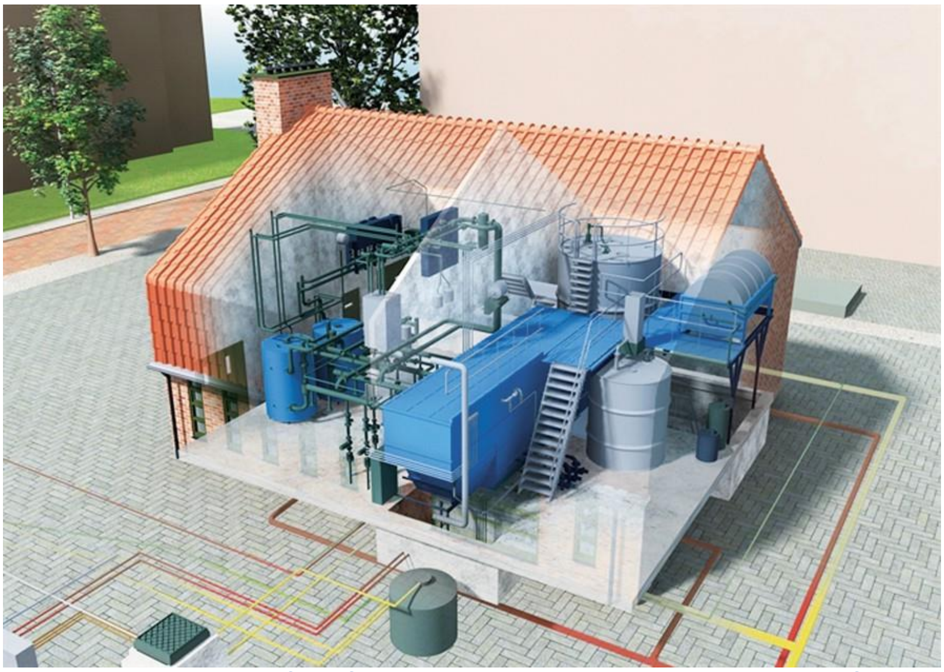

Figure 5.6. Impression of the facility building in Noorderhoek. Reprinted from Groenblauw (n.d.).

[p] Based on 3.5 hectare for 100,000 p.e. (Blom, 2014).

5.3 Functional dimension

The key findings of the assessment of the DESAH system in the functional dimension are presented in Table 5-IX. The results for the two included assessment aspects are discussed in detail in the following two subsections.

Table 5-IX. Overview of the key findings for the product specifications and actual performance of the DESAH system in the functional dimension.

Aspect	Product specifications	Actual performance
Durability and reliability	Life time expectancy of 15 years.	
	No climatic influences.	
	Technical errors mostly occur in the vacuum system.	Technical errors have occurred in the collection, distribution, treatment and resource recovery components.
		Energy recovery was not able for several periods due to errors.
Operation and maintenance	System operation requires low effort and skills.	Work load: 16 hours per week.
	System maintenance requires a trained technician.	Required skill level: Advanced intermediate vocational education (MBO+).
		The organization of the O&M activities was inadequate.
	Maintenance mainly comprises the cleaning of the components.	Maintenance mainly comprises of fixing technical errors.
	Remotely monitoring of the system functionality is possible.	

5.3.1 Durability and reliability

Product specifications

Since the DESAH system comprises a range of components, the practical life time of the system is hard the predict. For example, a UASB reactor lasts much longer than the pumps or small moving components in the system. For projective computations a life time expectancy of 15 years is assumed (Metz, 2020).

Besides, the DESAH system is regarded as a relatively stable waste water treatment technology. The system is closed from the outside environment, except for the effluent emissions. Therefore, the DESAH system is not subject by climatic influences such as temperatures, precipitation and evaporation (Hermans, 2014).

However, technical errors could occur within the system. Compared to the conventional waste water management, the reliability of the black water transport is essentially difference (Hermans, 2014). The vacuum system for transport carries some potential weaknesses in terms of technical errors. Telkamp (2018) lists these four expected risks related to the vacuum system:

1. Faulty connections of black water sources (toilets) to the greywater transport pipes during renovation of the homes.
2. Leakages of the vacuum system, resulting in insufficient suction.
3. Adjustments in the placements of vacuum sewers due to changes in the public area. This might result in:
4. Wrong scaling of the vacuum sewage pipes. Which leads to sewer blockages.

Actual performance

The actual life time of the DESAH system in Noorderhoek is not known yet. However, the technical life time expectancy of 50 years is followed in the life cycle assessment of Debucquoy & ’t Lam (2018).

Table 5-X. Observed technical errors in the DESAH system during 2012-2014 and 2014-2017.

System component	2012-2014	2014 - 2017
Vacuum toilets		Malfunction (≥1 occurrence) of 2% of toilets (unspecified).
Kitchen grinders	Malfunction of several grinders due to faulty installation.	Malfunction (≥1 occurrence) in 11% of grinders (unspecified).
Waste water collection well	Clogging due to FOG and sludge accumulation.	
Vacuum system (unspecified)		8 Errors due to dirty sensors.
Vacuum piping		1 blockage due to soil subsidence or faulty construction.
Vacuum pump		Coarse material (screws and parts of drywall) in pump.
Treatment components (unspecified)	Multiple small errors, mainly due to a too high water level in components.	
OLAND reactor		Malfunction (unspecified). Solved by software adjustments.
Struvite reactor		Clogging (unspecified).
Biogas transport piping		No biogas collection possible for a total duration of 3 months (over 5 times). Cause: water condensation in transport piping.
Heat exchanger		Out of order for 4 months. Cause: Fault in component settings

De Wit et al. (2018) and Wiersma & Meulman (2014) monitored the technical errors in the DESAH system in Noorderhoek. The results of the observed errors are summarized in Table 5-X. The main causes for the system errors were faulty installations, wrongful end-user behavior and late maintenance. The errors in the biogas transport piping and the heat exchanger had the largest impacts on the performance of the system. During the non-operative periods of these components, the related energy could not by recovered. Important to note is that the lost energy recovery is not taken into account during the composition of the energy balance (subsection 5.2.4). Furthermore, all errors that were observed during the monitoring periods have been solved effectively.

5.3.2 Operation and maintenance

Product specifications

Theoretically, the operation of a DESAH system requires relatively low effort and time. Metz (2020) also mentions that no specific training is required for daily operation. For a waste water treatment system in The Hague comprising of a few components of the entire DESAH system, the housekeeper without a technical background does visual checks of the system functionality on daily basis. However, the total time commitment depends on the amount of treatment modules that are included in the system. It is assumed that the time commitment does not proportionally increase with the size of the system and waste water load (Hermans, 2014). There is economies of scale in terms of the operation effort.

Additionally, the effluent quality needs to be monitored every week. Approximately three times a year small maintenance activities are performed by a trained technician. Major periodic maintenance activities exists of the removal of floating fat from the UASB reactor and the rinsing of the vacuum pumps and sewers (DESAH BV, n.d.-c; Metz, 2020). If maintenance of the vacuum system is required, it is important to make clear arrangement with the end-users, since the toilet and kitchen grinders cannot be used for the time being (Hermans, 2014).

Furthermore, the performance and functionality of some components are able to be monitored remotely. These components are monitored automatically via sensors and the observations are online transmitted to the supervising organization. If required, the supervisor can remotely adjust system settings (Metz, 2020).

Actual performance

The O&M related responsibilities in Noorderhoek are divided over four stakeholder parties. The housing association Elkien (formerly De Wieren) is responsible for the waste water collection components in the houses, and the residents are responsible for properly using the in-home components; the municipality Súdwest-Fryslân is responsible for the waste water transport from the houses to the treatment system; and the water board Wetterskip Fryslân is responsible for the treatment of the waste water. Additionally, the energy recovery components are under the responsibility of Elkien, but the O&M of the technical components are outsourced to a commercial party. However, the division of the responsibility appeared to bring complications for the execution of the O&M. The distribution and demarcation of the tasks were perceived as unclear (Hermans, 2014).

Wiersma & Meulman (2014) evaluated the executed operation activities for the initial DESAH system during 2012-2014. The work load of the regular activities was around 16 hours a week. The majority (approximately 11 hours) was related to water quality monitoring and data management. The skill level for these activities were considered to fit a person with an Advanced intermediate vocational education (MBO+) (Hermans, 2014).

During 2012-2014, the maintenance activities comprised of reparations or adjustments to solve the technical errors (see Table 5-X). It appeared that knowledge and skills related to maintaining the vacuum system was not always sufficient. Only few experienced technicians exists in the Netherlands, since vacuum system for the collection of waste water is a relatively new technology. Hence, the training of technicians is recommended (Wiersma & Meulman, 2014).

5.4 Economic dimension

The key findings of the assessment of the DESAH system in the economic dimension are presented in Table 5-XI. The results for the two included assessment aspects are discussed in detail in the following two subsections.

Table 5-XI. Overview of the key findings for the product specifications and actual performance of the DESAH system in the economic dimension.

Aspect	Product specifications	Actual performance
Investment costs	74.5% of total costs: €64 p.e.$^{-1}$ year^{-1}	69% of total costs: €61 p.e.$^{-1}$ year^{-1}
	Majority of the costs are for collection & distribution components.	Costs are more evenly divided over collection, distribution and treatment components.
Operational costs	25.5% of total costs: €22 p.e.$^{-1}$ year^{-1}	31% of total costs: €27 p.e.$^{-1}$ year^{-1}
	Most costs are for the operation of the treatment components.	Most costs are for the operation the of treatment components.
		Major operational costs savings come from energy recovery.

5.4.1 Investment costs

Product specifications

Garrido-baserba et al. (2018) performed a detailed economic analysis on the expenditures for a decentralized waste water system similar to the DESAH system. The calculated expenditures for capital were calculated to be €1,932 p.e.$^{-1}$ for the entire system with a technical life time of 30 years. Annually, that would be €64.40 p.e.$^{-1}$. Approximately 79% of these investments are required for the waste water collection and distribution components. The other 21% of the investment costs are for the purchase of the treatment components, of which the UASB reactor requires the largest share (see Table 5-XII). The investment costs of a WWTP system calculated by Garrido-baserba et al. (2018) were 23% less compared to the decentralized system.

Table 5-XII. Proportional cost breakdown for a decentralized system similar to the DESAH system. Costs savings from water savings, energy recovery and nutrient recovery are not included. Data from Garrido-baserba et al. (2018).

Component	Investment costs (% of total costs)	Operational costs (% of total costs)
Treatment components		
UASB reactor	11.2	6.8
OLAND RBC	0.2	3.8
Struvite reactor	0.1	0.2
Grey water treatment	4.6	6.2
Collection and distribution components		
Black water vacuum system (no kitchen grinder)	16.1	7.4
Grey water distribution	42.4	1.2
Total	**74.5**	**25.5**

Actual performance

De Graaf (2018) computed the annual depreciation costs for the capital investment in Noorderhoek. The calculations are based on the situation where the DESAH system is operating on full design capacity (1530 p.e.) with a technical life time of 15 and 30 years for different components. The results are presented in Table 5-XIII together with the annual investments costs per person for a conventional WWTP (30,000 p.e.).

The investment costs are €61.09 p.e.$^{-1}$ year^{-1} for the DESAH system in Noorderhoek. Regarding the product specifications, the investment costs are similar to those in the financial analysis of Garrido-baserba et al. (2018). The investment costs of the DESAH system in Noorderhoek are €25.53 p.e.$^{-1}$ year^{-1} higher than those from the WWTP. The main difference is made by the required costs for the sanitation components within the houses. Although there are costs for in-home sanitation in the situation with the conventional WWTP (e.g. when a toilet bowl needs to be replaced), these are not included in the comparison.

Furthermore, it is important to realize that the represented costs of the DESAH system are shared among 1530 person. In reality, 79 p.e. (in 2014) and 327 p.e. (in 2017) were connected to the system. Dividing the total costs over these numbers would result in considerably higher annual costs per p.e. However, the investments for the treatment of the waste water of 1530 p.e. are already made. Hence, it is financially beneficial in Noorderhoek if more households are connected to the DESAH system.

Table 5-XIII. Overview of the financial costs of the DESAH system operative for 1530 p.e., and a WWTP with 30,000 p.e. connected. Costs are in € p.e.$^{-1}$ year^{-1}. Data from De Graaf (2018).

Costs item	Investment costs Noorderhoek (1530 p.e.)	Operational costs Noorderhoek (1530 p.e.)	Investment costs WWTP (30,000 p.e.)	Operational costs WWTP (30,000 p.e.)
Treatment components	24.37	58.30	20.45	27.29
Distribution components	14.90	4.46	15.11	1
Sanitary and sewers in houses	21.82	-	-	-
Biogas recovery	-	-12.20	-	-
Water savings	-	-9.11	-	-
Small-sized organic waste avoidance	-	-14,00	-	-
Sub total	**61.09 (69%)**	**27.45 (31%)**	**35.56 (56%)**	**28.29 (44%)**
Total	**88.54**		**63.85**	

5.4.2 Operational costs

Product specifications

The operational costs of the decentralized high-tech waste water treatment systems are comprising of the wages for the operator; the reparation, replacement and cleaning costs; energy input costs; and the analyses of the system performance. However, operational costs savings are also made by the DESAH system. The recovery of biogas and thermal energy could save the costs for grid energy input to the system and the households (subsection 5.2.4). Additionally, the water bill for the end-user is reduced since the potable water use is potentially reduced by up to 32 liter per year (subsection 5.2.2). Furthermore, the recovered struvite has a market value of €188 to €763 per tonne, since it can be used as an agricultural fertilizer (Molinos-Senante et al., 2011).

Garrido-baserba et al. (2018) calculated the operational costs for a decentralized waste water treatment system similar to the DESAH system. The proportional costs per system component are presented in Table 5-XII. On annual basis, the operational costs are calculated to be €22.04 p.e.$^{-1}$. These yearly costs are 10% higher than the yearly operational costs of a WWTP (i.e. €20.02 p.e.$^{-1}$) calculated by Garrido-baserba et al. (2018). Important to note is that the potential financial savings from resource avoidance and recovery are not included among the operational costs for both the decentralized system and the WWTP.

Actual performance

Similar to the investment costs, the annual operation costs are presented in Table 5-XIII. The operational costs of the DESAH system in Noorderhoek are €62.76 p.e.$^{-1}$ year^{-1} and the savings/avoided costs are €35.31 p.e.$^{-1}$ year^{-1}. Thus, the net operation costs are €27.45 p.e.$^{-1}$ year^{-1} if 1530 p.e. are connected. The majority of the costs are related to the treatment components. About 78% of the operation costs are for the labor wages, sludge deposition, electricity and added chemicals (De Graaf, 2018). As expected from the product specifications, the cost savings originate from biogas recovery and the avoided potable water use. Additionally, costs are avoided due to the reduced domestic green waste that has to be deposited and processed in the conventional way. Besides, no financial benefits from the thermal energy recovery are included in the calculation.

In the practical case of Noorderhoek, no financial advantages are made from the struvite production. According to Metz (2020), the struvite production is insufficient for profitable return. Only when considerably larger DESAH systems will be designed, the inclusion of the sale of struvite becomes relevant for the economic value of the system.

Compared to the operational costs of the conventional WWTP and the computations of Garrido-baserba et al. (2018), the DESAH system in Noorderhoek requires twice the amount per person. However, the financial savings in Noorderhoek equipoise the difference.

Nonetheless, the summed costs for investments and operation in Noorderhoek exceed those that are made for the conventional WWTP. According the Metz (2020), the net economic balance of the DESAH system becomes more advantageous if the savings from the thermal energy are included.

5.5 Sociocultural dimension

The key findings of the assessment of the DESAH system in the sociocultural dimension are presented in Table 5-XIV. The results for the two included assessment aspects are discussed in detail in the following two subsections.

Table 5-XIV. Overview of the key findings for the product specifications and actual performance of the DESAH system in the sociocultural dimension.

Aspect	Product specifications	Actual performance
Community involvement	Adequate behavior and sufficient knowledge are required for good usage of in-home components.	Residents are informed about the system usage.
	Motivation of the end-users leads to improved system performance.	Better involvement of the residents prior to the system implementation is desired.
Acceptance		Overall, the residents are satisfied and proud with the system. Here, the facility building plays a key role.
	Modern vacuum toilets produce a similar sound volume as a conventional toilet. However, it is another type of sound.	A part of the residents have concerns about the noise of the vacuum toilet. But, most are satisfied with the design of the bowl.
		Experiences with the kitchen grinder are both positive and negative on various topics.
	No odor nuisance from treatment system.	

5.5.1 Community involvement

Product specifications

In the implementation and operation phase of the DESAH system, it is difficult to involve the local community with executive tasks. The design and maintenance activities require expert level skills and knowledge for adequate performance. However, the end-users play an important role in the in-home waste water generation and collection. Adequate usage of the in-home components is required for the system to operate at a sufficiently high level and to avoid technical errors. Compared to a conventional system, the vacuum toilet and kitchen grinder are newly added components. Hence, the usage of these components is unfamiliar to most end-users during the first period of an implemented DESAH system. Therefore, informing the end-users from the start of the system operation is important.

Besides of providing the end-users sufficient knowledge about adequate usage, the motivation and commitment to actually do so is decisive as well. Motivated and committed users are often more tolerant to problems that are a burden to their comfort (Hegger et al., 2008). Motivation and commitment can be created by informing the community about the objectives and advantages of the DESAH system. Metz (2020) suggested the implementation of a digital feedback feature (e.g. a smartphone app). The performances of the DESAH system can be communicated to the end-users, so they are aware of the benefits. Since the performance of the system components is already partly automated and digitalized, the establishment of a digital feedback system is relatively uncomplicated.

Actual performance

The housing association Elkien plays a crucial role in the involvement of the community as it is the point of contact between the governments, technical actors, and the residents (Hermans, 2014). For example, Elkien provides a website with usage manuals, user experience, system expert videos and an overview of the DESAH system benefits (website: waterschoon.nl). Hence, the residents of Noorderhoek are supported in executing their responsibility concerning the proper collection by adequately separating the black and grey waste water and the small-sized kitchen waste.

Additionally, an evaluation of the end-user experience in 2014 concluded that more attention should have been paid to the providence of information prior to the system implementation (Hermans, 2014). For example, demonstration events of the vacuum toilet and kitchen grinder for future connected residents are recommended. So, the residents are more convenient about the expectations of living with the DESAH system. No information is available about the implementation of this recommendation.

Also, a questionnaire among the residents of the first 32 households indicated that the residents would have liked to have more say in the decision making during the entire process of the Noorderhoek project. However, it is not clear on what aspects their say was lacking according to the residents (Naus & Van Vliet, 2012).

5.5.2 Acceptance

Product specifications

The acceptance among the local community is depending on expected and experienced end-user comfort. When implementing the DESAH system, some potential differences of the end-user experiences are involved compared to the traditional waste water management system. The in-home separation of waste water stream requires different use and maintenance of the sanitary appliances. Since the Dutch residents are assumably unfamiliar with the vacuum toilet and kitchen grinder, trust must built first to accept them. Important for gaining trust is that these sanitary appliances function reliably and do not reduce the comfort of the end-user. The reliability is indicated by technical errors that impact the routine of the end-user.

In regards of the end-user comfort, the main concern among stakeholders of the DESAH system is the noise disturbance for the local community (Hegger & Van Vliet, 2010). The concern for noise disturbance originates from the sound of the vacuum toilets. In 2007, noise measurements pointed out that the vacuum toilets installed in a DESAH system produced a sound of 96 decibel (dB). This was 12 dB more than a conventional toilet (Telkamp et al., 2008). However, the expectation of the hard noise from the vacuum toilet is outdated. Modern vacuum toilets produce sounds that are not louder than a conventional toilet (Run4Life, 2020). Metz (2020) stated that sounds of 75 dB are produced. Although, the vacuum toilet produce a different type of sound. The end-users have to accustom themselves to this new sound.

Furthermore, the reduction in comfort from odor nuisance is virtually excluded. Metz (2020) stated that odor filters are included in the DESAH systems. Only if an odor filter does not functions properly, unpleasant smells might escape the treatment components.

Actual performance

In general, the residents of Noorderhoek are satisfied with and proud of the DESAH system (De Wit et al., 2018). The outside facility building for the treatment components plays a key role in the positive association with the unique sanitary system. The central building is symbolic for the residents, and is referred to when proud experiences are shared with other people (Hermans, 2014).

A questionnaire among the residents of the first 32 households of the Noorderhoek neighborhood showed that the impact of the implemented system on the end-user comfort is partly negative and partly positive. On the one hand, the majority of the responding residents experiences the sound production of the vacuum toilets as a nuisance. Approximately half of the respondents are even worried that they might disturb their neighbors by flushing the vacuum toilet. Note that this applies to the older version of the vacuum toilet, that produces a sound of 96 dB. On the other hand, the majority of the residents are satisfied with the design and experience the toilet as a hygienic during use compared to a conventional toilet. Furthermore, most residents do not find it difficult to clean the bowl (Naus & Van Vliet, 2012).

Thirty percent of the residents experience the noise of the kitchen grinder as the most bothersome feature, while 19% experience the blockages of the grinder as largest nuisance. However, most users indicate that the sound is something that they got used to. It is not seen as a reason to disregard the use of the grinder. The experienced contributions of the grinder to the end-user comfort are the ease-of-use, the contribution to circularity and an increased level of hygiene in the kitchen (Steenhuisen, 2020). Also, residents experience less effort due to the kitchen grinder, since less domestic green waste has to be taken out. Additionally, the reduction of green waste collection in the bin results in the avoidance of unpleasant odors in or near the homes (Naus & Van Vliet, 2012).

Also, the provided information about the DESAH system and the usage of the toilet and kitchen grinder lead to a comfortable feeling among the residents concerning the modern features in their homes. Appendix 6 contains examples of the provided information to the residents. Although, not all residents were satisfied with information providence on paper. More practical demonstrations in advance could have contribute to a better imaging of the impact of the DESAH system on the end-user's daily routine (Naus & Van Vliet, 2012).

6. Compliance of the actual performances

The outcomes of the study provide detailed information about the theoretical product specifications of the VSSF-CW and the DESAH systems. Additionally, detailed information on the practical performance of the two technologies in four Dutch cases is provided as well. The product specifications and practical performance of both technologies are assessed via 11 distinctive aspects over four complementary dimensions. The outcomes almost entirely cover the product specifications of both technologies on all 11 aspects. Only the product specifications of the spatial requirements were too limited for adequate comparison with the actual performance.

However, more information was lacking about the performance in the practical cases. Results are limited for the practical performances of the energy balance and investment costs of the VSSF-CW technology; and of the nutrient recovery of the DESAH system. Hence, no credible conclusions could be formulated for the compliance in these aspects. Nevertheless, most aspects are covered with information on the practical performance. Whether the actual performance complies with the product specifications is indicated in Table 6-I.

Table 6-I. Compliance of the actual performance with the product specifications for each aspect.

Dimension	Aspect	Compliance with product specifications?	
		VSSF-CW	DESAH system
Environmental	Water treatment performance	**Y / N+**	**Y**
	Local water balance	**Y**	**Y / N–**
	Nutrient recovery	**Y**	**n.c.**
	Energy balance	**n.c**	**Y**
	Spatial requirements	**Y / N-**	**n.c.**
Functional	Durability and reliability	**Y / N**	**n.c. / N-**
	Operation and maintenance	**N–**	**Y / N**
Economic	Investment costs	**n.c.**	**Y / N-**
	Operational costs	**Y / N–**	**Y / N**
Sociocultural	Community involvement	**Y**	**Y**
	Acceptance	**Y**	**N**

By following the criteria for the determination of the compliances as described in section 3.3, not all aspects could be indicated with a singular concluding symbol. For several aspects of the technologies, compliance has partly been confirmed and partly disproved. Also for several aspects, the determination of the compliance could partly not be concluded. Therefore, these aspects are provided with two symbols that conclude on the compliance of the actual performance with the product specifications (see Table 6-I).

7. Discussion

7.1 Interpretation of the results

This study aimed to evaluate how the product specifications will manifest during the actual performance of decentralized domestic waste water technologies when they are applied in Dutch urban areas. Therefore, the product specifications and actual performance of the vertical subsurface flowing constructed wetland (VSSF-CW) system and the DESAH system were analyzed in four Dutch practical cases. The results of the analysis show that the decentralized domestic waste water treatment technologies assessed each have a specific set of theoretical product specifications. Additionally, the results support the anticipated discrepancy between these theoretical product specifications and how they manifest in practice. Overview of the key results and the compliances of the actual performance with the product specifications is provided in Appendix 7 (VSSF-CW) and Appendix 8 (DESAH system).

7.2 Limitations

Although the two selected technologies are rather distinctive, the question raises whether the assessment of these two technologies covers the evaluation of all available decentralized domestic waste water treatment technologies. Regarding the resulting differences in compliances between the VSSF-CW and the DESAH system, it is highly likely that similarly diverse outcomes would be generated if other technologies are analyzed with the same methodology. Therefore, no general answer can be formulated to the research question that considers 'decentralized waste water technologies' as one singular concept. However, this study demonstrates that a particular answer can be formulated if the research question would address the technologies and their aspects individually.

Additionally, the applicability of the outcomes for each Dutch situation might be questioned. Uncertainty is caused by the specific context in the four selected practical cases. The composition of end-users in the selected cases are probably not the exact representation of the average Dutch neighborhood. The three assessed cases of the implemented VSSF-CW technology have all been established in ecological neighborhoods, with residents that explicitly choose to be involved. The DESAH system in Noorderhoek is subject to a relatively large share of elderly end-users, since the neighborhood included a nursing house for elderly people. The end-user behavior, involvement, acceptance and the waste water composition are assumed to be different in these ecological neighborhoods and nursing houses compared to average Dutch households. Hence, the composition of end-users in a neighborhood probably affects the performance of a decentralized waste water treatment technology. Nevertheless, it is seemingly impossible to find practical cases that precisely represent the average Dutch neighborhood, especially if the targeted technologies are only scarcely implemented.

Capodaglio et al. (2017), performed a similar analysis of the product specifications of decentralized waste water technologies. The assessment framework that they applied included the impacts of the technologies to human health as an additional dimension. Regarding the main objective of waste water management concerning the protection of human health, the inclusion of this dimension seems evident. During this study, moderate attention is paid to health related topics. The removal of microbial pathogens, health risk prevention in water reuse applications and the presence of mosquitos are discussed. However, a more prominent position for the impacts of the decentralized treatment technologies to public health would be appropriate.

Furthermore, the assessment framework applied by Capodaglio et al. (2017) included the aspects of institutional acceptance to the sociocultural dimension. From their analysis appeared that the potential for resource recovery and financial advantages are decisive factors for the acceptance among institutional and administrative stakeholders. Since the decision of the implementation of the technologies is strongly dependent on the willingness of the institutional stakeholders, it is appropriate to include the institutional acceptance as an aspect in the assessment framework (Bracken et al., 2005).

Moreover, Capodaglio et al. (2017) mention that during the design of a decentralized waste water system the compliance with the prevailing legislative conditions is important to be taken into account. Regarding the findings in this study, several inconsistencies can be found between the prevailing legislative regulations (subsection 2.1) and the regulations in the practical cases. For instance, the residents in all four cases pay charges to the water board for the centralized waste water treatment. However, if the waste water treatment is decentralized, and less or no waste water is transported to the WWTP, the residents are still obligated to pay the same charges to the water board. This even holds when the municipality and housing associations bear all responsibilities for the decentralized treatment system, because the Dutch legislative framework is designed that way. This raises questions among residents and municipalities (Coopmans & Van Ruijven, 2020; Gemeente Groningen, 2016). Such constraints from the legislation framework are important to the implementation of a decentralized waste water treatment technology. However, the aspect of the legislative conditions is not taken into account in this study.

7.3 Relevance of the outcomes

Despite the limitations discussed above, the outcomes provide a step towards a complete evaluation of decentralized domestic waste water treatment technologies in Dutch urban context on neighborhood scale. The results of the assessment of 11 essential aspects give insight in the potential benefits and limitations of the VSSF-CW and the DESAH system. Additionally, the results show several examples of the practical performance of these two technologies applied in the Netherlands. During current and future waste water decentralization projects in similar context, the gained insights can be taken into account by waste water experts and decisive stakeholders. So, the result facilitate an improved deliberation on the most suitable waste water treatment technologies. This value especially applies for the Dutch municipalities that are currently in the design phase and consider the implementation of the VSSF-CW or the DESAH system.

Additionally, this study provides quantitative results for several aspects in both the theoretical and practical performances. For example, the aspects in the environmental dimension are provided with quantitative results. These results can be used in future modeling and design studies of the two technologies. Although, the ones who adopt these data should be aware of the fact that the data do not representative the practical performance of the technologies in the context of their specific case.

Regarding the available scientific literature concerning decentralized waste water technologies, this study stands out through the inclusion of both the theoretical specifications and the actual performance in four distinctive dimensions. In studies where the performance of a decentralized waste water treatment technology is assessed in a specific context, only one or two of dimensions are included. Most of these studies focus on either the treatment efficiency, the reuse of the effluent or the economic aspects. The performance in the sociocultural aspects are hardly reviewed. Besides, the studies concerning the implementation of a decentralized waste water system in a specific context rarely take the 'lessons learned' into account from practical cases in similar context.

An example of an exception is the study of Brix et al. (2011). The study aimed to show the potential of the integration of extensive constructed wetland systems in touristic areas. In order to do so, the performance of an operative constructed wetland system on the island of Koh Phi Phi in Thailand was assessed. Although Brix et al. (2011) did not use an explicit assessment framework, the results presented are on aspects that are similar to those in this study. Brix et al. (2011) concluded with the difference between the expectations in advance and actual practice of the decentralized waste water technology on Koh Phi Phi. Also, the importance of the inclusion of the institutional dimension was confirmed.

7.4 Recommendations for further research

In order to approach completion of the answer to the research question of this study, future research should reduce the limitations discussed above. Here, the three main recommendations are provided for future scientific research in the field of decentralized waste water technologies.

The first recommendation is to assess the aspects that were not able to be concluded during this study. For the energy balance and investment costs of the VSSF-CW system, too little data was available on the actual performance in the practical cases. That also applied for the actual performance of the nutrient recovery of the DESAH system. Since data on these performances are expected to be quantitative and rather straightforward (e.g. electricity consumption and mass of struvite production), these aspects could be monitored relatively easily.

The second recommendation is to complement the assessment framework with one dimension that relates to the impacts on public health and one that relates to the institutional conditions. By including the public health dimension, future assessment of the technologies could attribute more weight to the original objective of waste water management (i.e. protect human health from hazardous constituents in waste water). By including the institutional conditions, the outcomes of the assessment are expected to give added insights into the institutional burdens for implementation of the technologies.

The third recommendation is to analyze other decentralized waste water treatment technologies with the improved assessment framework. By assessing the product specifications and the actual performance of all the technologies in Dutch urban context, an answer can be given to the main research question, which considers decentralized waste water technologies as one concept.

8. Conclusion

This study aimed to contribute the selection of the most suitable treatment technology for the implementation in Dutch urban areas. In order to do so, the study addressed the following research question:

> *Does the actual performance of decentralized domestic waste water treatment technologies comply with their product specifications when they are applied in urban areas in the Netherlands at neighborhood scale?*

In order to provide an answer to the research question, the vertical subsurface flowing constructed wetland (VSSF-CW) and the DESAH system were analyzed within an assessment framework. The assessment framework consisted of 11 aspects divided over four dimensions (environmental, functional, economic and sociocultural). Furthermore, the actual performances were collected by an evaluation of four practical cases in the Netherlands.

Regarding the discussed limitations of the study, no credible answer to the research question can be formulated. The main reason for this is that the two assessed technologies are not fully representative for all decentralized domestic waste water treatment technologies. Therefore, it is recommended to add more technologies to the assessment. Furthermore, the outcomes are limited to the environmental, functional, economic and sociocultural dimensions. Although this provided a comprehensive overview, the product specifications and the actual performances in the human health dimension and institutional dimension are lacking.

Nevertheless, this study provide credible outcomes to the product specifications and actual performance of the VSSF-CW and the DESAH system in the environmental, functional, economic and sociocultural dimensions. The results for each of the two technologies show full, partial, no or partial-no compliance on 9 of the 11 aspects.

So, if the research question was limited to these two decentralized treatment technologies and to the four dimension of the assessment framework, the research question would be answered with that the actual performance of the technologies partly comply with the product specifications.

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Appendix 1. Semi-structured interview outline

- Date:
- Location:
- Name:
- Case:
- Actor role:

<u>Introduction</u>

- Explanation of the research and background
- Background case
  - History (including technological adjustments)
  - Overarching project
  - Other urban water flows
  - Type of neighborhood and inhabitants
- Meaning of interview and assent for use of information

<u>Technology</u>

- Types of treatment
- Waste water separation at source
- System configurations

<u>Functional dimension</u>

- Households/people connected and capacity
- longevity of technology
- Technical errors
- Operation & Maintenance
  - Who
  - Time and effort
  - Skill-level

<u>Economic Dimension</u>

- Operation and Maintenance costs
- Costs for energy
- Investment expenses
- Costs savings from resource recovery
- Additional costs/savings?

(Continued on next page)

(Semi-structured interview outline - continued from previous page)

Environmental dimension

- Treatment efficiency
    - Standard parameters
    - Pharmaceuticals
    - Microbial pathogens
- Effluent potentials
- Effects on potable water demand
- Nutrient removal / recovery
- Energy input
- Energy recovery
- Spatial requirements of technology
- Integration in urban area

Sociocultural dimension

- Experience of end-users
- Perspective of end-users
- Nuisances:
    - Sound
    - Smell
    - Pests
    - Usage
- Related health issues
- Involvement of end-user
    - Stage (planning, design, O&M..)
    - Involvement over time

Miscellaneous

- Economy of scale effects
- Points of attention for further development
- Any benefits or contributions to add
- Any risks to add
- Availability of further (written) information or persons of interest

Appendix 2. Climatic and seasonal influence on the VSSF-CW system performance

Influence of precipitation and evaporation

The generation of the effluent is affected by the fluctuations in effluent generation. The top of a VSSF-CW filter bed is open to the atmosphere. Hence, the amount of treated water is influenced by evapotranspiration and precipitation. Since the evapotranspiration and precipitation rates are varying over the seasons and years, the amount of water treated by a VSSF-CW is not entirely stable. Evapotranspiration leads to less effluent production and precipitation leads to more effluent production. Moreover, the contaminants in the waste water are less influenced by these climatic factors. Hence, the waste water in the filter bed is practically more concentrated due to evapotranspiration and more diluted due to precipitation (STIBA, 1998). According to Van Oirschot (2020), 1 m² of filter bed is able to treat about 50 liter domestic waste water per day. In warm and dry periods, 10% to 20% of the water load might be evaporated from the filter bed in the Netherlands. Precipitation might occur through the entire year. In 2015, the total precipitation in the Netherlands was 854 liter m^{-2} on average (CLO, 2016). This is 4.7% of the treated waste water in a VSSF-CW system functioning on full capacity. However, on average nine days of heavy rainfall (> 50mm per day) occur in the Netherlands on average (CLO, 2020). With 50 mm of precipitation on a filter bed, the waste water is diluted one-to-one.

Seasonal robustness

The bacterial communities that are responsible for the microbial degradation of the contaminants are negatively influenced by low temperatures in the soil. Nonetheless, the bacterial communities function sufficiently even during the winter in the Netherlands. This is caused by the relatively high temperature of the domestic waste water at the soil bed (8 to 10 °C [Van Oirschot, 2020]). Normally, this prevents the soil bed from freezing (Ecofyt, n.d.-b; Kilian Water, n.d.-b). Additionally, the organic matter in the soil (e.g. from the helophytes) act as nutrient source for the bacteria. Hereby, the bacteria can survive for a certain period without being fed by the waste water (STIBA, 1998; Van Oirschot, 2020).

Appendix 3. VSSF-CW filter clogging

The main limitation for the functionality of the VSSF-CW is that several components are prone to clogging (Hoffmann et al., 2011; Tilley et al., 2014). Although most large-sized materials are removed during the pre-treatment in the septic tank and FOG traps, some materials (e.g. hairs, clothes particles and food residues) proceed to the water distribution components. These components are vulnerable to clogging from sludge and material that do not fit through the discharge openings in the pipelines (Nanninga, 2011). Additionally, the filter bed may also clog due to extensive formation of biofilm or the accumulation of solids on the surface of the substrate grains (see Figure A.4). The extensive formation of biofilm occurs mainly in the top layer of the filter bed, if the organic load in the supplied waste water is too high (Weedon, 2003), hence the infiltration of waste water is ceased at these locations. As a result, the supplied waste water ponds on top of the clogged filter bed columns and the infiltration rate increases in the unclogged columns. The latter results in a decreased HRT, causing a reduced treatment efficiency. To resolve a clogged top layer, one should puncture holes in the substrate to stimulate the infiltration of the ponded waste water and halt the water supply for several weeks to eliminate the biofilm (Van Oirschot, 2020). As a filter bed clogs up too often, the system designer might consider more intensive pre-treatment measures to reduce the organic load on the filter bed (Caselles-osorio & Garcia, 2007).

If ferrous matter is added to the substrate, the filter bed might clog near the drainage pipe at the bottom of the column. The iron oxidizes as a result of the intermittent aerobic conditions in the filter. As a result, the iron oxide precipitates as solid particles in the substrate. As these particles accumulate in the bottom layer, the substrate and the drainage pipe will be blocked off (de Matos et al., 2018). To avoid clogging caused by the oxidation reaction, the system should be designed in such a way that the ferrous substrate material is continuously in anaerobic conditions (i.e. under the water level) (STIBA, 1998).

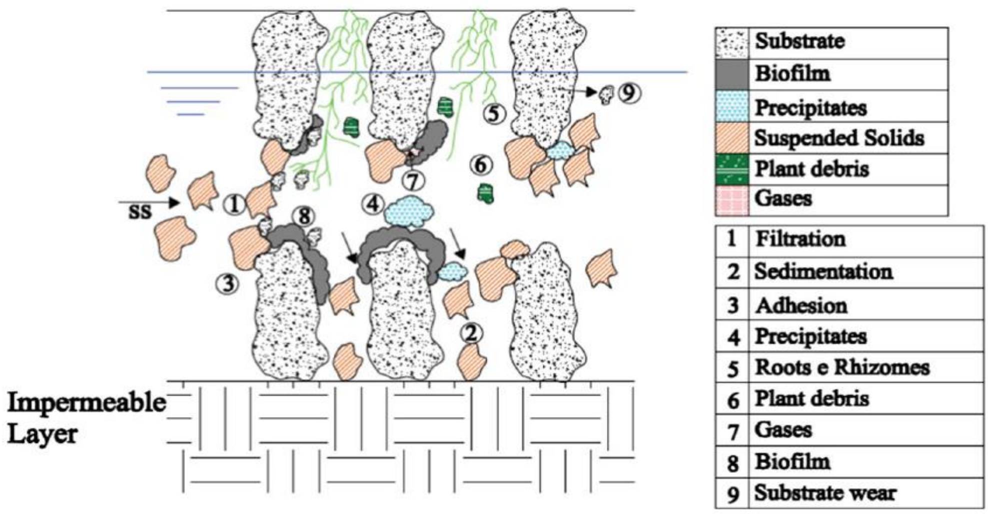

Figure A.1. Clogging processes in constructed wetlands. Here displayed for the horizontal subsurface constructed wetland. However, the processes are similar for the vertical orientation (VSSF-CW). Adapted from de Matos et al. (2018).

Appendix 4. Instructions for disposal of constituents (Polderdrift)

polderdrift
Ecologisch Wonen Rijkerswoerd

GEBRUIKSINSTRUCTIE POLDERDRIFT:
LIJST VAN STOFFEN DIE WEL OF NIET DE AFVOER IN MOGEN:

WEL:

Afwaswater
Ontvettingsmiddelen op waterbasis
Poetsmiddelen
Spoelwater
Spiritus
Waswater

NIET:
Ammonia
Bakolie
Bleekwater
Boenwas
Chloor
Frituurvet
Glansmiddel
Gootsteenontstopper
Koperpoets
Cosmetica (remover/nagellak)
Olie of vet
Schoensmeer
Schoonmaakmiddelen met fosfaten
Stopbaden (foto)
Toner (poeder)
Vlekverwijderingmiddelen op waterbasis
Wasmiddelen met fosfaten
Zilverpoets

BESLIST NIET:

Aceton
Accuzuur
Afgewerkte olie
Autowas
Benzeen
Benzine
Bestrijdingsmiddelen
Cfk's
Fotofixeer
Foto-ontwikkelaar
Houtverduurzamingsmiddelen
Inkten
Insecticiden
Kettingsmeer
Kitten
Kwastreiniger
Kwastenontharder
Lampolie
Lijm
Medicijnen
Meubelolie
Nagellak
Petroleum
Plamuur
Remolie
Remover
Smeermiddelen
Smeervet
Terpentine
Terpentijn
Thinner
Tolueen
Verf (ook op waterbasis)
Verfafbijtmiddel
Verfverdunner
Vlekkenverwijderingsmiddel
Vloerenwas
Wasbenzine
Zoutzuur
Zware metalen als lood, koper, zink, kwik etc.
Overige stoffen met onduidelijke herkomst en/of samenstelling

Appendix 5. Photo reportage of the Polderdrift field visit on June 30, 2020

Top view of the filter bed with the helophytes.

Positions of the grey water and effluent collection wells (in red circles).


Front view of the shed where the circuit box, the control panel for the water pumps and the sediment trap are harbored.


Compost bin for garden waste.

Appendix 6. Instructions for use of the vacuum toilet and the kitchen grinder (Noorderhoek)

Informative handouts concerning the instructions for the vacuum toilet (left) and the kitchen grinder (right). Handouts reprinted from Waterschoon (n.d.).

Appendix 7. Overview of the key findings for the VSSF-CW technology

Aspect and compliance	Product specifications	Actual performance (All traditional VSSF-CW)
Water treatment efficiency	Effluent quality meets IBA class IIIb standards.	Effluent quality meets IBA class IIIb standards.
	NO_3 removal is limited.	Good N removal.
Y / N+	Pathogen removal > 99%	Pathogen removal of 1.4 - < 4.9 log
	Forced aeration systems have improved BOD and possibly improved N removal.	
	Forced aeration systems have a proper contribution to the removal of pharmaceuticals.	The system in Drielanden has a proper contribution to the removal of pharmaceuticals.
Local water balance	Effluent can be discharged to local surface water.	Effluent is discharged to local surface water.
Y	Effluent can be reapplied for toilet flushing, showering, laundry, garden irrigation or outside cleaning.	In Polderdrift, the effluent is reapplied for toilet flushing.
Nutrient recovery	Recovery via helophytes harvesting.	Helophytes harvested.
Y	Reuse as fertilizer is feasible on large scale.	Composted locally or discarded.
Energy balance	Traditional systems: < 4.4 kWh p.e.$^{-1}$ year^{-1}	EVA-Lanxmeer: 14.2 kWh p.e.$^{-1}$ year^{-1}
n.c.	Forced aeration systems: 20-30 kWh p.e.$^{-1}$ year^{-1}	
Spatial requirements	Traditional systems: 2.4 – 5 m² p.e.$^{-1}$	Polderdrift: 2.6 m² p.e.$^{-1}$ EVA-Lanxmeer: < 6.5 m² p.e.$^{-1}$ Drielanden: 2.7 m² p.e.$^{-1}$
Y / N-	Forced aeration systems: 0.75 m² p.e.$^{-1}$	
	Provides opportunities for multi-beneficial integration with local (living) environment.	Contributes to biodiversity.
Durability and reliability	Life time expectancy - Traditional systems: 25 year. - Forced aeration systems: 35 years.	Current time in operation 8 to 24 years.
Y / N	Traditional system is prone to clogging.	Multiple errors in the various system components (clogging, leakages, system regulation, weeds).
	Resilient to climatic influences.	
		Operation in Polderdrift is halted due to end-user sentiment (fear of health risk).

Continued on next page

Operation and maintenance **N-**	Traditional system: relatively easy O&M, no high skill level required.	Residents are able to perform daily operation and several semi-annual maintenance activities.
		Some maintenance activities are outsourced due to specific requirements (e.g. rinsing of components and research).
	Traditional system: Guidelines for periodic O&M activities provided.	
	Forced aeration systems: Similar O&M activities; higher-level skills required for maintenance of air supply system.	
Investment costs **n.c.**	Traditional system: €411-507 p.e.⁻¹	Initial investment in EVA-Lanxmeer: €681 p.e.⁻¹
	Forced aeration system: €92-408 p.e.⁻¹	
Operational costs **Y / N-**	Traditional system (annually) - O&M: €6-40 p.e.⁻¹ - Energy: < €1 p.e.⁻¹	Normal annual O&M and energy costs - Polderdrift: €16-50 p.e.⁻¹ - EVA-Lanxmeer: €33 p.e.⁻¹
		1 time research costs Polderdrift: €48 p.e.⁻¹
		1 time component replacement costs - Polderdrift: €114 p.e.⁻¹ - EVA-Lanxmeer: €31 p.e.⁻¹
	Forced aeration system (annually) - O&M: €15-22 p.e.⁻¹ - Energy: €4-7 p.e.⁻¹	
Community involvement **Y**	Possible to involve in O&M activities.	Involvement in daily O&M activities.
		Residents involved during design and planning phase of the water system.
	Provides opportunities for education and recreation.	Residents provide guided tours concerning the water system.
Acceptance **Y**	No increased nuisance from mosquitos and odor.	No mosquito nuisance, little odor nuisance.
	Only potential health risks if effluent is exposed to human during reuse.	No unfavorable impacts on public health; Polderdrift: fear concerning the spread of SARS-CoV-2 virus in the reuse system.
	Possible coloration of effluent due to humic acids.	
		Well-perceived technology by local community.

Appendix 8. Overview of the key findings for the DESAH system

Aspect	Product specifications	Actual performance
Water treatment efficiency **Y**	Effluent quality meets IBA class IIIb standards.	Only the total phosphorus (TP) concentration in effluent substantially exceeds the legal standards during 2012-2014.
		After 2014, TP removal is greatly improved by adding more magnesium salts to the struvite reactor.
	High effluent quality, especially if membrane filtration is included.	
		Substantial contribution to the removal of a range of pharmaceuticals.
Local water balance **Y / N-**	Saves 23% to 27% of the total potable water consumption due to vacuum toilet.	Saves to 4% to 30% compared to the Dutch average potable water consumption.
		In-home dislocating of waste water results in an higher volume of black water than expected, and a lower volume of grey water.
	Effluent quality is sufficient for discharge to local surface water	Effluent is discharged to local surface water.
	Toilet flushing, showering, laundry, garden irrigation, outside cleaning or thermal energy carrier are feasible reuse applications for the effluent.	
Nutrient recovery **n.c.**	Struvite production of 9.7 to 12.0 gram per day.	K-struvite is produced due to ammonium deficit; no available data on the production rate.
	Produced struvite is a beneficial agricultural fertilizer.	No information on the reapplication of the produced K-struvite.
Energy balance **Y**	Require electrical and thermal energy.	Heat and biogas recovery play a major role for the positive energy balance.
	Heat can be recovered from the waste water.	
	Biogas can be recover, as a byproduct of the UASB reactor.	
		Without technical errors, the net energy balance is positive (energy producing)
Spatial requirements **n.c.**	Vacuum system and treatment components require most space.	Facility building requires up to 3.5 times less surface area compared to a WWTP.
	Treatment facilities can be placed in various locations.	

Continued on next page

Overview of the key findings for the DESAH system – continued from previous page

Durability and reliability	Life time expectancy of 15 years.	
	No climatic influences.	
n.c. / N-	Technical errors mostly occur in the vacuum system.	Technical errors have occurred in the collection, distribution, treatment and resource recovery components.
		Energy recovery was not able for several periods due to errors.
Operation and maintenance	System operation requires low effort and skills.	Work load: approximately 16 hours per week.
Y / N	System maintenance requires a trained technician.	Required skill level: Advanced intermediate vocational education (MBO+).
		The organization of the O&M activities was inadequate.
	Maintenance mainly comprises the cleaning of the components.	Maintenance mainly comprises of fixing technical errors.
	Remotely monitoring of the system functionality is possible.	
Investment costs	74.5% of total costs: €64 p.e.$^{-1}$ year^{-1}	69% of total costs: €61 p.e.$^{-1}$ year^{-1}
Y / N-	Majority of the costs are for collection & distribution components.	Costs are more evenly divided over collection, distribution and treatment components.
Operational costs	25.5% of total costs: €22 p.e.$^{-1}$ year^{-1}	31% of total costs: €27 p.e.$^{-1}$ year^{-1}
	Most costs for operation of treatment components.	Most costs for operation of treatment components.
Y / N		Major operational costs savings from energy recovery.
Community involvement	Adequate behavior and sufficient knowledge are required for good usage of in-home components.	Residents are informed about the system usage.
Y	Motivation of the end-users leads to improved system performance.	Better involvement of the residents prior to the system implementation is desired.
Acceptance		Overall, the residents are satisfied and proud with the system.
N	Current vacuum toilet produces a similar sound volume as the conventional toilet, but another type of sound.	A part of the residents have concerns about the noise of the vacuum toilet, and most are satisfied with the design of the bowl.
		Experiences with the kitchen grinder are both positive and negative on various topics.
	No odor nuisance from treatment system.	