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Abstract

South Africa is classified as being the 30th driest country in the world and is regarded as a water scarce country. However, for the urban residents of the City of Cape Town, the ability to reduce their municipal water consumption through initiatives, other than simply using less water, is limited. Hence, there is a need for affordable, simple and compact technical solutions which allow urban populations residing in high density developments to make use of alternative sources of water, specifically greywater, to reduce their municipal water demand.

Existing commercial technologies were considered, together with the socio-economic and technical constraints of an illustrative middle-income urban household in the City of Cape Town (CoCT). It was found that each commercial technology considered satisfied some, but not all, constraints characteristic of the household. For instance, the treatment device may produce treated water of a high quality. However, it may not be financially feasible for the consumer. Of the commercial technologies considered, there is no single commercial technology which can offer a complete solution within the socio-economic and technical constraints of the household. For this reason, the opportunity exists to produce an innovative technical solution.

The proposed greywater treatment device consists of four cylindrical chambers in a vertical arrangement. Raw greywater enters the top chamber and treated greywater is extracted from the bottom chamber forming the base. The treatment processes undergone as the greywater flows through the treatment device include, in the following order, pre-filtration, biological treatment (Activated Sludge), clarification, filtration and disinfection. The process is driven by a combination of gravity and electrical energy. The proposed design is constructed using readily available materials and components. It is modular in its construction, allowing for easy maintenance, assembly and an increase in design flexibility. Evaluating the design against the same evaluation criteria stipulated for the existing commercial technologies showed that the proposed design may be an appropriate solution for the illustrative middle-income household within the City of Cape Town and is a novel technical solution.

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Abbreviations

Abbreviation	Description
<i>ADWF</i>	Average dry weather flow
<i>ANO</i>	Ammonia nitrifying (i.e. autotrophic) organisms
<i>AS</i>	Activated Sludge
<i>BOD</i>	Biochemical oxygen demand
<i>CAPEX</i>	Capital expenditure
<i>CoCT</i>	City of Cape Town
<i>COD</i>	Chemical oxygen demand (of all organic material)
<i>DSVI</i>	Diluted sludge volume index
<i>FSA</i>	Free (NH ₃) and saline (NH ₄ ⁺) ammonia
<i>MPN</i>	Most Probable Number of coliform per 100 ml
<i>NPV</i>	Net present value
<i>NTP</i>	Normal Temperature and Pressure, as defined by the International Union of Pure and Applied Chemistry (IUPAC).
<i>OHO</i>	Ordinary heterotrophic organism
<i>OPEX</i>	Operational expenditure
<i>PWWF</i>	Peak wet weather flow
<i>RBCOD</i>	Readily biodegradable COD
<i>SST</i>	Secondary settling tank
<i>SSVI</i>	Stirred sludge volume index
<i>TBD</i>	To be determined
<i>TKN</i>	Total Kjeldahl nitrogen
<i>TOC</i>	Total Organic Carbon
<i>TP</i>	Total Phosphorus (organic and ortho-phosphates)
<i>TSS</i>	Total suspended solids
<i>VSS</i>	Volatile suspended solids
<i>WAS</i>	Waste activated sludge

Nomenclature

Symbol	Description	Units
A	Level of public acceptance	%
A_{SST}	Projected area of secondary settling tank	m^2
b_{HT}	Specific endogenous mass loss rate of OHOs at temperature T	d^{-1}
b_{H20}	Specific endogenous mass loss rate of OHOs at 20°C	d^{-1}
b_{nT}	Specific endogenous mass loss rate of ANOs at temperature T	d^{-1}
b_{n20}	Specific endogenous mass loss rate of ANOs at 20°C	d^{-1}
CA	Treatment capacity score	%
CP	Perceived level of complexity score	%
D	Diameter	m
F	Treatment device footprint score	%
f_{at}	Fraction of OHOs in the sludge as TSS	$mgVSS/mgTSS$
f_{av}	Fraction of OHOs in the sludge	$mgVSS/mgVSS$
f_{cv}	COD to VSS ratio of the sludge	$mgCOD/mgVSS$
f_{EH}	Unbiodegradable fraction of OHOs	$mgVSS/mgVSS$
f_h	Factor which takes radial mixing into account for UV disinfection (0.5 to 1)	-
f_{iOHO}	Fraction of OHO cell mass which is inorganic	$mgISS/mgVSS$
f_{lmp}	Lamp end life factor for UV disinfection (0.65 to 1)	-
f_n	Fraction of OHO cell mass which is Nitrogen	$mgN/mgVSS$
$f_{n'a}$	Fraction of total influent TKN which is FSA	$mgFSA - N/mgN$
FN_{ne}	Effluent nitrate flux	$mgNO_3 - N/l$
f_{ns}	Ratio of influent TKN to influent COD	$mgN/mgCOD$
FN_{ti}	Influent TKN flux	mgN/d
FN_{te}	Effluent TKN flux	mgN/d
$f_{n'uso}$	Fraction of total influent TKN which is unbiodegradable and soluble	mgN/mgN
f_{O_2}	Fraction (by volume) of Oxygen present in the atmosphere	%
FO_c	Carbonaceous oxygen demand per day	mgO/d
FO_n	Nitrification oxygen demand per day	mgO/d
FO_t	Total oxygen demand per day	mgO/d
f_p	Fraction of OHO cell mass which is Phosphorus	$mgP/mgVSS$
FP_{te}	Effluent TP flux	mgP/l
FP_{ti}	Influent TP flux	mgP/d
$f_{p'uso}$	Fraction of influent TP which is organic, unbiodegradable and soluble	mgP/mgP

f_q	Ratio of PWWF to ADWF	-
$f_{S'up}$	Particulate unbiodegradable fraction of total influent COD	$mgCOD/mgCOD$
$f_{S'us}$	Soluble unbiodegradable fraction of total influent COD	$mgCOD/mgCOD$
FS_{bi}	Influent flux of biodegradable COD	$mgCOD/d$
FS_{ti}	Influent flux of total COD	$mgCOD/d$
f_t	Fouling factor used for UV disinfection (0.5 to 0.9)	-
FX_{Ii}	Influent flux of unbiodegradable organic particulates	$mgVSS/d$
FX_{IOi}	Influent flux of inorganic matter	$mgISS/d$
f_{xm}	Minimum unaerated sludge mass fraction to allow for nitrification	-
f_{xt}	Unaerated sludge mass fraction	-
FX_t	Flux of TSS in WAS	$mgTSS/d$
FX_v	Flux of VSS in WAS	$mgVSS/d$
HR	Perceived health risk score	%
I	Inflation	%
I_{avg}	Average UV lamp intensity	$\mu W/cm^2$
i	Discount rate	%
K_{nT}	Nitrification half saturation coefficient at temperature T	mgN/l
K_{n20}	Nitrification half saturation coefficient at 20°C	mgN/l
K_s	Half saturation coefficient for RBCOD	$mgCOD/l$
K_v	Kinetic OHO growth constant	$l/mgVSS \cdot d$
MX_{BH}	Total mass of OHO biomass in reactor	$mgVSS$
MX_{EH}	Total mass of endogenous residue in reactor	$mgVSS$
MX_I	Total mass of inert organic particulates (from influent) in reactor	$mgVSS$
MX_{IO}	Total mass of inorganic particulates in reactor	$mgISS$
MX_t	Total mass of TSS in reactor	$mgTSS$
MX_v	Total mass of organic matter of activated sludge (i.e. VSS) in reactor	$mgVSS$
n	Flux theory constant	$l/gTSS$
n_x	End user acceptability normalising factor	-
N_{ae}	Effluent concentration of FSA	$mgFSA - N/l$
N_{ai}	Influent concentration of FSA	$mgFSA - N/l$
N_{an}	Ammonia concentration, per litre influent, available for nitrification	$mgFSA - N/l$
N_{ousi}	Concentration of organic unbiodegradable soluble Nitrogen in influent	mgN/l
N_{ne}	Effluent nitrate concentration	$mgNO_3 - N/l$
N_{rem}	Percentage of Nitrogen removal by AS treatment process	%

N_s	Concentration of Nitrogen exiting the reactor as WAS, per litre of influent	mgN/l
N_{te}	Effluent TKN concentration	mgN/l
N_{ti}	Influent TKN concentration	mgN/l
O_c	Carbonaceous oxygen demand per litre influent per day	$mgO/l.d$
O_n	Nitrifier oxygen demand per litre influent per day	$mgO/l.d$
O_t	Total oxygen demand per litre influent per day	$mgO/l.d$
OUR_c	Carbonaceous oxygen utilisation rate	$mgO/l.h$
OUR_n	Nitrifier oxygen utilisation rate	$mgO/l.h$
OUR_t	Total oxygen utilisation rate	$mgO/l.h$
P_{ousi}	Concentration of organic unbiodegradable soluble Phosphorus in influent	mgN/l
P_{rem}	Percentage of Phosphorus removal by AS treatment process	%
P_s	Concentration of Phosphorus exiting the reactor as WAS, per litre of influent	mgP/l
P_{ti}	Influent TP concentration	mgP/l
P_{te}	Effluent TP concentration	mgP/l
Q_{AC}	Volumetric air demand	l/min
Q_e	Effluent flow rate	l/d
q_l	SST overflow (i.e. load)	m/h
Q_i	Influent flow rate	l/d
$Q_{i,pwwf}$	Peak wet weather influent flow rate	l/d
Q_R	SST underflow recycle rate	l/d
Q_w	Waste water flow rate	l/d
R_{hn}	Hydraulic retention time	$days$
R_s	Sludge retention time (i.e. sludge age)	$days$
R_{sm}	Minimum sludge retention time to allow for nitrification	$days$
R_t	Expected nett cash inflow for year t	$Rands$
S_b	Reactor COD concentration	$mgCOD/l$
S_{bi}	Influent COD concentration	$mgCOD/l$
S_f	Safety factor (nitrification)	-
S_{te}	Effluent COD concentration	$mgCOD/l$
S_{ti}	Influent COD concentration	$mgCOD/l$
T	Temperature	$^{\circ}C$
t	Expected nett cash inflow R_t for year t	$Years$
t'	Hydraulic retention time for UV disinfection	$Seconds$



V_o	Flux theory constant	m/h
V_p	Reactor volume	l
V_s	Particulate settling velocity	m/h
w_o	End user acceptability water quality score	-
w_x	End user acceptability weighting factor	-
X_{BH}	Biomass (OHO VSS) concentration in reactor	$mgVSS/l$
X_{Ii}	Influent flow inert particulate concentration	$mgVSS/l$
X_{IOi}	Influent flow inorganic particulate concentration	$mgISS/l$
X_R	Underflow concentration	$mgTSS/l$
X_t	TSS concentration in reactor	$mgTSS/l$
X_v	VSS concentration in reactor	$mgVSS/l$
Y_{Hv}	Mass of biomass (OHO) formed per milligram of COD utilized	$mgVSS/mgCOD$
ρ_O	Density of Oxygen (at NTP)	kg/m^3
θ	Actual contact time of fluid with UV lamp	<i>Seconds</i>
μ_{AmT}	Maximum specific growth rate of ANOs at temperature T	d^{-1}
μ_{Am20}	Maximum specific growth rate of ANOs at 20°C	d^{-1}
μ_{HT}	Maximum specific growth rate of OHOs at temperature T	d^{-1}
μ_{H20}	Maximum specific growth rate of OHOs at 20°C	d^{-1}

1. Introduction

South Africa is classified as being the 30th driest country in the world and is regarded as a water scarce country. For a consumer to reduce their consumption of municipal water, sourcing water from an alternative water source is the only other option available once the consumer has reduced their consumption to the minimum amount possible through behavioural change. Although some urban consumers have taken the initiative to reduce their municipal demand, whether it be through rain water harvesting, groundwater extraction, or greywater recycling, these are the minority. For a significant proportion of the population, the following limitations exist when attempting to use water from alternative sources:

Societal constraints:

- Not owning the property on which he/she resides

Economic constraints:

- Cost of ownership of water treatment technologies (CAPEX and OPEX)

Technological constraints:

- Technological solutions offered are often complex
- Technological solutions typically require large amounts of space, yet the majority of a population within an urban environment resides in residential dwellings with limited space (such as in high density developments)

Hence, considering the above, the ability of the urban population to reduce their municipal consumption through initiatives other than simply using less water is limited. This problem is social, economic and technical.

1.1 Research Problem Statement

There is a need for affordable, simple and compact technical solutions which will allow urban populations residing in high density developments to make use of alternative sources of water and reduce their municipal water demand. Hence, the research problem is phrased as follows:

“What technological solutions exist, that are affordable, simple and compact, which will enable urban populations residing in high density developments to make use of alternative sources of water? Can these solutions be improved upon or does the opportunity exist to produce an innovative technical solution?”

1.2 Research Objectives and Questions

The research objectives, and their associated questions, are listed below. The literature study served to provide the information necessary to answer each research question associated with their respective research objective. The scope of this literature study is illustrated in the form of a conceptual framework (Figure 1).

- Determine what alternative sources of water are available to the urban consumer
 - What (social, economic, geographic) characteristics define the City of Cape Town (CoCT) urban consumer?
 - Under what conditions will the urban consumer be willing to make use of alternative sources of water?
 - What alternative sources of water exist for the urban water consumer?
 - What laws and regulations govern the use of alternative sources of water in urban areas?
- Investigate treatment solutions which will allow the consumer to make use of alternative sources of water
 - What is the most appropriate alternative water source for the urban consumer?
- Identify technological solutions making use of treatment processes and technologies which are affordable, simple and compact
 - What is the most appropriate treatment process for the CoCT consumer?
 - How will affordability, simplicity and compactness be defined?
- Determine the shortcomings of the current technological solutions offered
 - Will the current technological solutions be described qualitatively and/or quantitatively?
 - What analytical technique can be used to quantitatively evaluate the current technological solutions offered?
- Produce a prototype design which is able to provide a technological solution within the societal, economic and technological constraints
 - Will the proposed solution be evaluated qualitatively and/or quantitatively?
 - How will the superiority of the proposed design be proven?

1.3 Research Assumptions

The research assumptions made for each research objective are listed below.

- Determine the shortcomings of the current technical solutions offered
 - The consumer will not be concerned with the aesthetics of the treatment device itself.
- Produce a prototype design which is able to provide a technological solution within the societal, economic and technological constraints
 - The consumer will not be concerned with the aesthetics of the treatment device itself.
 - Evaluation of the proposed prototype design will be by means of a desktop study only and not by means of an experimental study (as such a prototype does not yet exist in the UCT laboratory). This is deemed to be sufficient for the purposes of this *minor* dissertation.

1.4 Key Research Outputs

The key research outputs for this minor dissertation are stated as follows.

- Provide a concise summary of existing technological solutions pertaining to the use of an appropriate alternative water source in urban residential settings.
- Define the suitability of the existing technological solutions to the urban population residing in the Cape Town Metro.
- Propose a novel technical solution (by means of a desktop study only), capable of meeting social, economic and technological constraints.

2. Literature Review

In the 20th century, water demand managers primarily focused on the development of new infrastructure for supplying water (from surface water sources), of drinking quality, to various populations. This infrastructure included dams, reservoirs and pipelines, all forming part of large water distribution networks (Gleick, 2003). In recent decades, however, drought and climate change are having a global impact, with many cities facing an increase in water demand (due to population growth) alongside a decrease in surface water availability. Hence, there is a global consensus among nations that ensuring water security will become one of the greatest challenges faced by humanity (WWAP, 2015). It is for this reason that cities are looking to establish alternative water sources as part of their water conservation efforts (Eslamian, 2016).

Alternative sources of water may include seawater, rain and wastewater (i.e. water reuse). However, given its high energy costs, desalination is not regarded as a global solution (“Megascale Desalination - MIT Technology Review,” n.d.). Rainwater harvesting and (treated) wastewater reuse are more attractive options (Jiménez & Asano, 2008). Countries which have made great strides in the inclusion of such alternative water sources, specifically water reuse, to meet ever increasing urban water demands include Namibia, Japan, Australia, Germany and China.

Many cities are now considering the decentralisation of wastewater treatment and reuse, at community level, alongside the use of water efficient technologies to decrease water demand. Water reuse together with water efficient equipment easily allow for significant reductions in water demand. Although existing wastewater treatment technologies are effective, these are very rarely shown to be economically viable for small communities, given the large capital investment and high operating costs (Wilcox et al., 2016).

Other technological solutions for water reuse have been more focused on the end user (i.e. the consumer), or more specifically, on the individual household. Such solutions allow for the onsite treatment of greywater, which is the most abundant of the wastewater streams (Chaillou et al., 2011). Currently, these solutions can be divided into two groups. The first group involves the use of water treatment technologies in rural settings with open spaces and at little cost. These solutions are simple and consume little to no electrical energy. The second group utilises water treatment technologies in developed residential areas at great cost. These solutions are often complex and may consume large amounts of energy. Despite the vast differences between the two groups of household-specific technologies, the underlying (biological) process responsible for affecting water treatment is very similar (with the latter aerobic and the former aerobic/anaerobic).

Solutions which are regarded as simple, affordable and consuming little to no energy often make use of basic (well-understood), naturally ventilated, biological and chemical treatment processes which can be of great benefit to small rural communities (Mandal et al., 2011). Research has shown that end users of such technological solutions are satisfied with their practicality, operability and maintainability. However, due to the presence of foul odours, these solutions require the availability of open space (Assayed et al., 2015), which is becoming more of a luxury in developed urban environments.

Technological solutions which use mechanically assisted aeration, avoiding the production of foul odours, are ordinarily sized to meet the requirements of a single household (4 to 10 person equivalents per day) and require significant capital expenditure. Such technologies also consume larger amounts of electrical energy than naturally ventilated solutions. In relation to their naturally ventilated counterparts, they are expensive and complex in their operability and maintainability.

Whilst the technological constraints are an important consideration in the generation of possible solutions, the importance of public perception and government policy cannot be understated. They are often critical in the successful implementation of not only water reuse, but in all water conservation initiatives. Several governments, such as Australia (Declan Hearne, n.d.), China (Lyu et al., 2015) and the Western Cape Government of South Africa (Cameron, 2014) have come to realise that public participation in water conservation and water reuse initiatives ultimately dictate their level of success.

Hence, it is obvious that technological solutions exist for both rural communities and (wealthy) suburban households. However, there may be no technological solutions appropriate for the majority of individuals residing within high density urban developments and with limited financial capabilities, such as in the City of Cape Town (CoCT). Any technological solution considered for the CoCT urban consumer must be capable of meeting both the technological and socio-economic constraints, if it is to have any success.

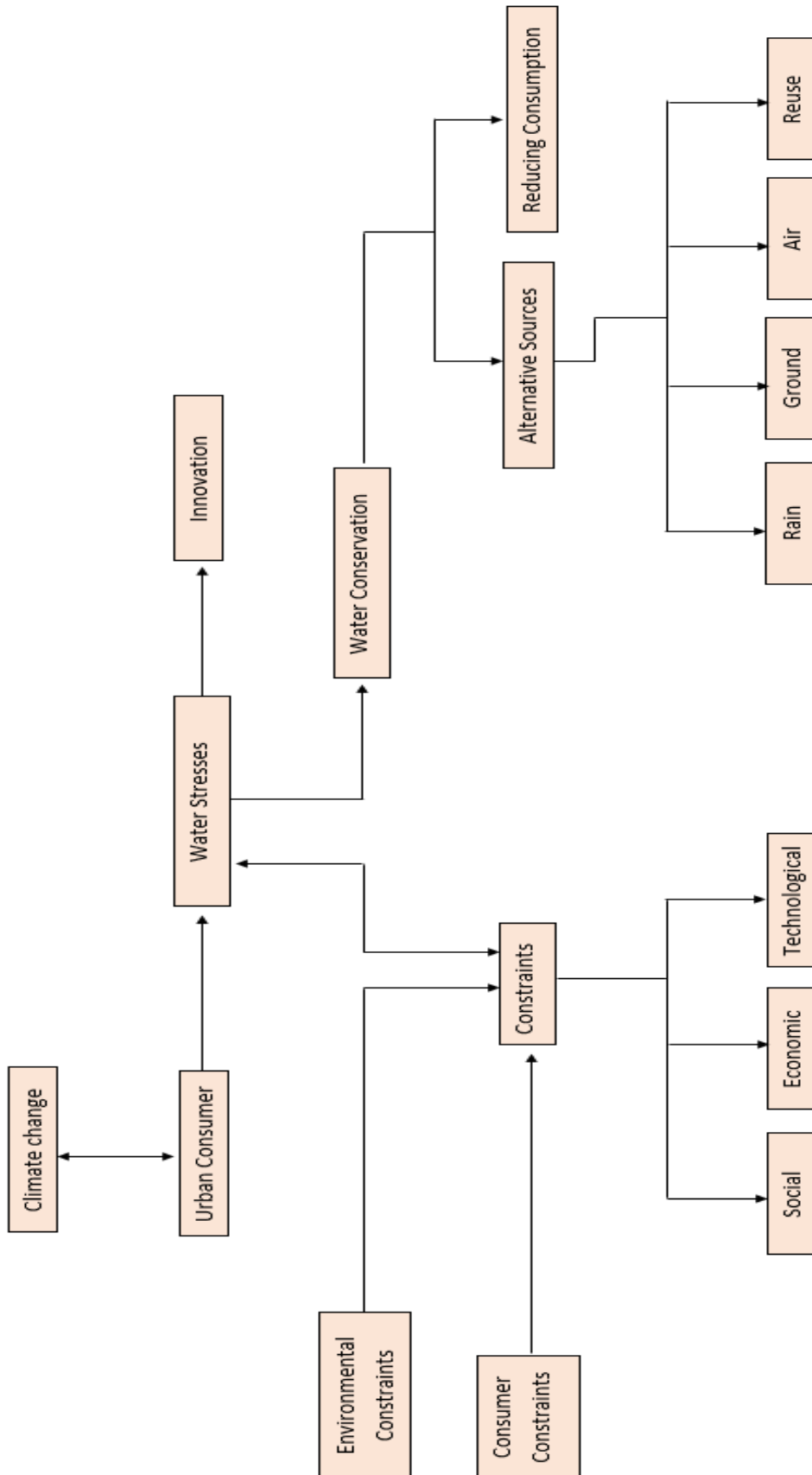


Figure 1: Conceptual framework for this literature study

2.1 Alternative urban water sources

2.1.1 The urban consumer in the City of Cape Town

The effects of climate change are becoming more evident with each passing year in the form of extreme weather patterns, such as frequent flooding, prolonged droughts and above average temperatures. This phenomenon is not only localised to a few countries, but instead is being experienced across the globe. One of the most concerning effects of climate change is the decrease in surface water availability. This is further exacerbated when combined with the degradation of the natural environment by human beings and an increased water demand, due to population growth.

Water stress is a result of the above which is experienced by the urban consumer, in the form of a less reliable municipal water supply, increased water tariffs and a deterioration of municipal water quality. The degree to which this is experienced by the consumer in a community is dependent upon endogenous and exogenous factors. To determine what alternative sources of water are available to the urban consumer in the area of study (i.e. Cape Town Metro), it is necessary to first establish key socio-economic and geographic characteristics which define the City of Cape Town (CoCT) urban consumer.

The City of Cape Town (also referred to as “The City”) has a Mediterranean climate, with monthly maximum summer and winter temperatures reaching an average of 27 and 18 degrees Celsius, respectively. The majority of rainfall typically occurs in the winter months, with a total annual rainfall averaging between 300mm and 600mm (South African Weather Service, n.d.). However, annual rainfall patterns have recently become unpredictable, with extreme weather phenomena being experienced.

As shown in Table 1 (below), water is made accessible to urban consumers in four ways: (i) piped supply inside a household (ii) piped supply into a yard (ii) communal supply (i.e. stand pipe) within 200m of the household (iv) communal supply farther than 200m away (CSIR, 2000). Generally, most CoCT residents have access to (municipal) water and electricity. With an increase in living standards among CoCT residents, water demand is expected to grow between 2 and 3.38% per annum (Currie et al., 2017). Also, the water consumption of low income households with stand pipe connections rarely exceeds 30 litres per day, whilst high income households easily exceed that figure (Rodda et al., 2011). Furthermore, this does not take into account instances in which a city is implementing water conservation and water demand management. In such cases, the average daily water demand per capita may be as low as 50 litres (e.g. “moderate” as indicated in Table 1) (Sunday Times, 2018).

Table 1: Water consumption in areas of South African cities equipped with standpipes, yard connections and house connections (CSIR, 2000)

Table 9.11: Water consumption in areas equipped with standpipes, yard connections and house connections (adapted from Department of Water Affairs & Forestry, (1992): Guidelines for the selection of design criteria)		
DOMESTIC WATER CONSUMPTION		
TYPE OF WATER SUPPLY	TYPICAL CONSUMPTION (l/c/d)	RANGE l/c/d
Standpipe (200 m walking distance)	25*	10 - 50
Yard connection	55	50 - 100
With dry sanitation		30 - 60
With LOFLOs		45 - 75
With full-flush sanitation		60 - 100
House connection (developed areas) #		60 - 475
Development level: Moderate	80	48 - 98
Moderate to high	130	80 - 145
High	250	130 - 280
Very high	450	260 - 480

Currie et. al (2017) performed an in-depth metabolic and resource study of the City of Cape Town, providing statistics relevant to the characterisation of the CoCT urban consumers. The city is estimated to have a population of 3.8 million people, with monthly household incomes ranging between R1 to more than R102 000 per month. These statistics are presented graphically in Figures 2 and 3 (below). The Western Cape Government defines a low-income household as earning R1 to R4 217.75 per month, a middle-income household as earning R4 217.83 to R33 741.75 per month, and a high-income household as earning more than R33 741.75 per month (City of Cape Town, 2016).

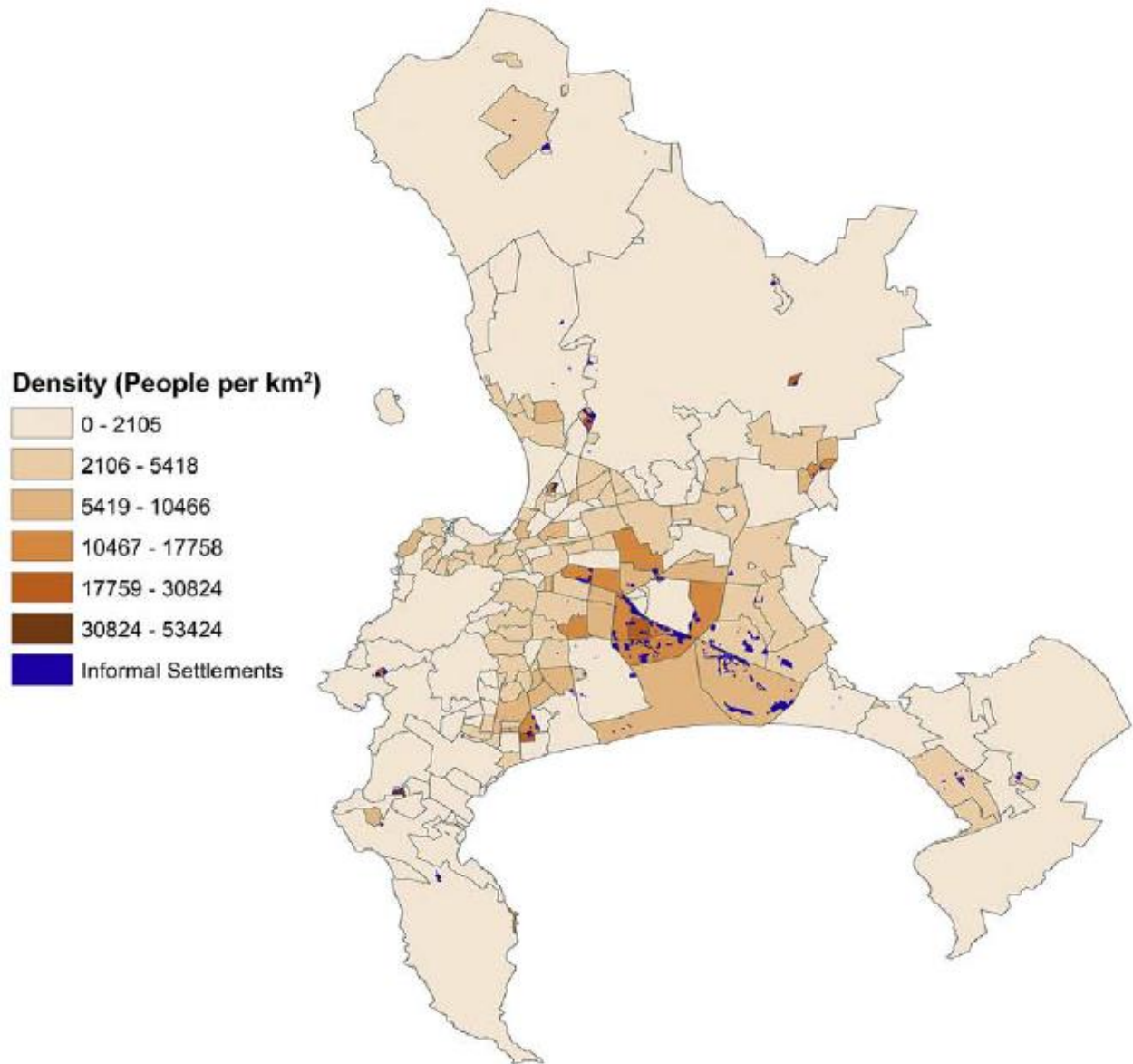


Figure 2: Population densities CoCT (Metro) (Currie et al., 2017)

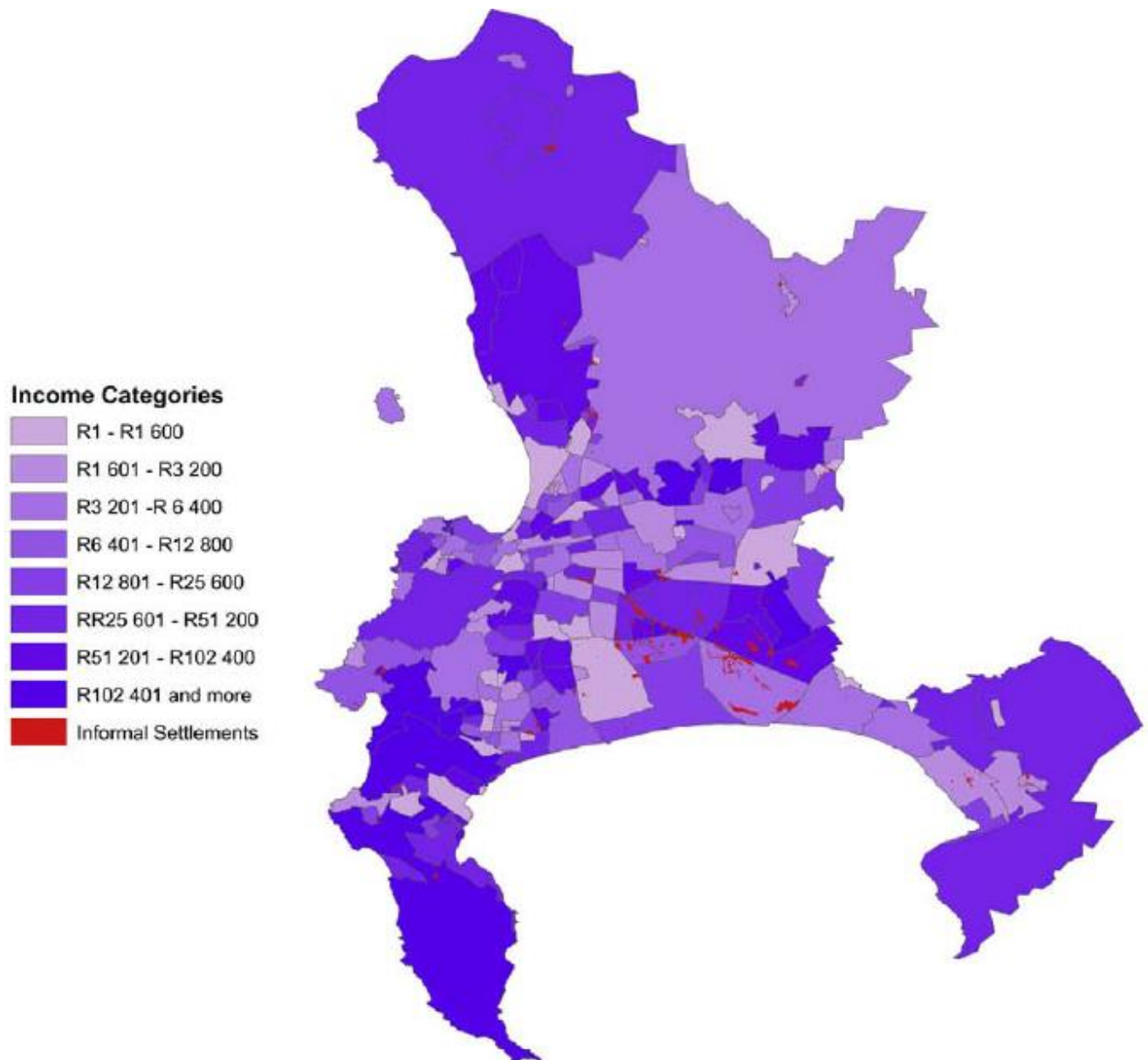


Figure 3: Monthly household income categories CoCT (Metro) (Currie et al., 2017)

House price inflation has increased significantly over the last 15 years in the Cape Town Metro, by almost 400% (Tarrant, n.d.), making them far more unaffordable than in areas outside of the metro (Graham et al., 2015). CoCT residents earning more than R51 200 per month are more likely to own the property on which they reside, with ownership estimated at 80%. For households earning less than R12 800 per month, home ownership is estimated to be 50%. For households earning less than R51 200 per month, home ownership estimated to be 65%.

Approximately 60% of the Western Cape population resides in houses on a separate stand, with the remainder either residing in flatlets, apartments, townhouses and traditional or informal dwellings (Graham et al., 2015). This proportion is expected to decrease as population density increases when moving towards the Central Business District (CBD).

When considering the distribution of water consumption within the City of Cape Town, illustrated by Figure 4 (below), approximately 65% of the water supplied to the City of Cape Town is consumed by residential households. As most (free standing) houses use water for outdoor activities as well as indoor activities, it comes as no surprise that these households constitute 55% of the City’s total water demand (Department of Water and Sanitation, 2018).

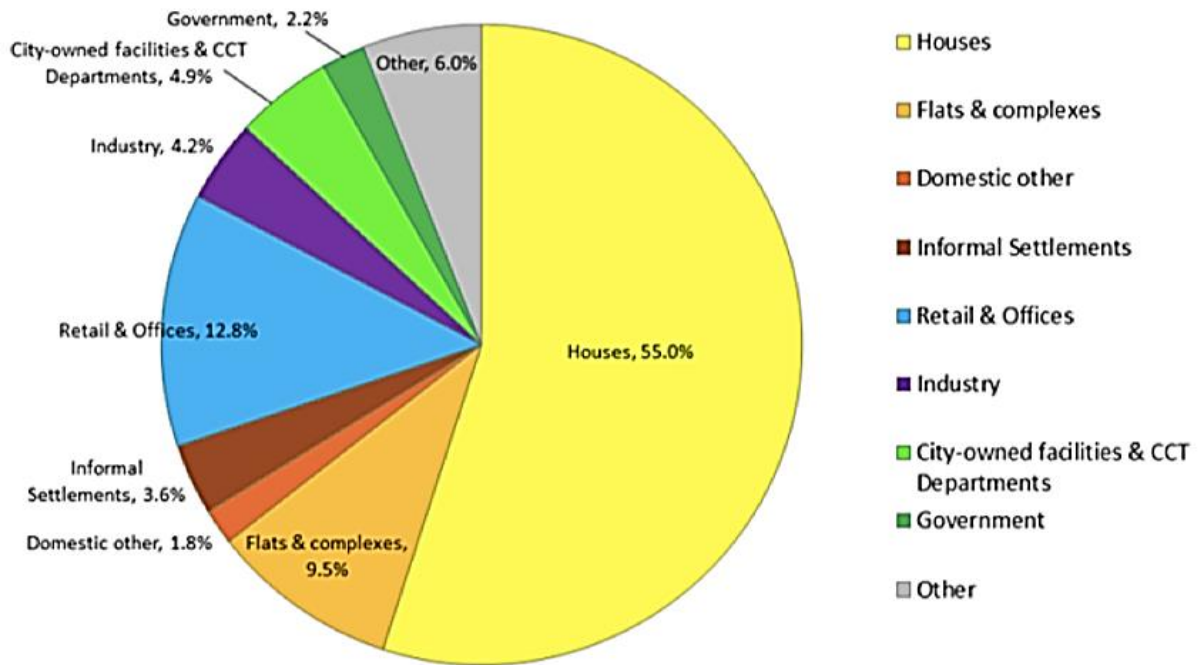


Figure 4: Distribution of potable water consumption within different sectors in the City of Cape Town, with 55% utilised by houses and 9.5% utilised by people residing in flats and complexes (Department of Water and Sanitation, 2018)

2.1.2 Urban participation and constraints

In a paper published by Domenech et. al (2010), public acceptance and participation in water conservation, including (grey) water reuse, is obtained where the following conditions (or a combination thereof) exist:

- Water shortages are experienced by the consumer
- Water tariffs are increased
- Legalisation of water reuse and guidelines are issued by government
- Mandatory requirements are stipulated by government for water conservation/reuse and are enforced
- Rebates are offered for the installation of water conservation and reuse technologies
- The public is well-educated with regards to possible health risks, operational changes and costs associated with water reuse
- Practising environmental conservation is a part of the community's culture

Ajzen (2001) proposes that a person's willingness to use recycled water depends upon three factors: attitude, perception and perceived ease or difficulty in implementing water reuse. Ultimately, a compromise between a consumer's level of comfort and convenience must be made when undertaking water conservation and water reuse. Furthermore, the consumer must be willing to accept responsibility for the management of such a system (Ajzen, 2001).

Perhaps one of the most understated factors dictating public participation is the perceived health risk(s), as this is closely related to the so called "yuck" factor (Seah, 2002). The "yuck" (i.e. disgust) factor describes the severity of a consumer's psychological and emotional response at the thought of using recycled water. Health risks may be reduced by either improving the quality of treated wastewater or by introducing a means to limit exposure to the treated wastewater (Rodda et al., 2011). In a study performed by Po et. al (2003), consumers participating in water reuse initiatives stated that the use of additional tertiary filtration within their own household aided in overcoming the "yuck" factor. Furthermore, people are far more willing to utilise (treated) wastewater originating from within, as opposed to outside of, their own household (Jeffery, 2001).

The study undertaken by Domenech et. al (2010) paid close attention to the socio-technical constraints determining public acceptance of greywater reuse technologies. A level of acceptance of greywater reuse, for toilet flushing, was obtained through a survey of several households currently employing greywater reuse systems for toilet flushing. The author concluded that the most significant drawbacks regarding greywater reuse, as indicated by the users through a number of

interviews and face-to-face discussions, include unpleasant odours, followed by aesthetics, reliability and cost.

A number of literature reviews have shown that water reuse projects are far more likely to succeed when providing treated wastewater for non-potable purposes, with residents' main concerns being odour, colour and/or sediment. It is also interesting to note that people generally expect to pay less for recycled water, as it is perceived to be water of a lower quality (Jiménez & Asano, 2008). The failure of several large scale water-reuse projects is also a reminder of how reliant their success is on public perception and political support (Po et al., 2003). Ultimately, most consumers have no objection to water recycling as long as treated water quality can be guaranteed. Table 2 (below) provides a useful summary of acceptable uses of treated wastewater.

Table 2: Percentage of consumers opposed to specific uses of recycled water from several studies (Po et al., 2003)

Source										
	ARCWIS (2002)	Sydney Water (1999)	Lohman & Milliken (1985)	Millikin & Lohman (1983)	Bruvold (1981)	Olsen et al. (1979)	Kasperon et al. (1974)	Stone & Kahle (1974)	Bruvold (1972)	
Sample Size (N)	665	900	403	399	140	244	400	1000	972	
Drinking	74	69	67	63	58	54	44	46	56	
Cooking	-	62	55	55	-	52	42	38	55	
Bathing	52	43	38	40	-	37	-	22	37	
Laundry	30	22	30	24	-	19	15	-	23	
Flushing	4	4	4	3	-	7	-	5	23	
Swimming	-	-	-	-	-	25	15	20	24	
Irrigation (dairy pastures)	-	-	-	-	-	15	-	-	14	
Irrigation of vegetables	-	-	9	7	21	15	16	-	14	
Vineyard irrigation	-	-	-	-	-	15	-	-	13	
Irrigation of parks	-	3	-	-	4	5	-	-	3	
Golf course irrigation	2	-	-	-	4	3	2	5	2	

In the study performed by Dominguez et. al (2017), using low-income households, acceptability of rainwater and greywater reuse were calculated to be 78% and 91%, respectively. Several drawbacks of greywater reuse were identified in the study (Table 3), the most significant being the production of unpleasant odours, followed by the breakdown of reuse systems and water aesthetics. Generally, as shown in Figure 5 and Figure 6 (below), the most acceptable end uses of rainwater by the consumer include toilet flushing, household cleaning and irrigation. When considering greywater reuse, most consumers find greywater reuse acceptable for toilet flushing. Findings by other authors provide the same conclusion (Oviedo-Ocaña et al., 2017; Ward et al., 2013). Dominguez et. al (2017) also sought to confirm the perception that low income households would place greater importance on cost and economic benefits of rainwater harvesting and greywater reuse systems. However, this was proven to be false. Instead, greater importance was placed on the volume of water that could be saved. Research conducted by James et. al (2016) showed that 70% of households were willing to invest a further 10% of their water bill towards water management devices.

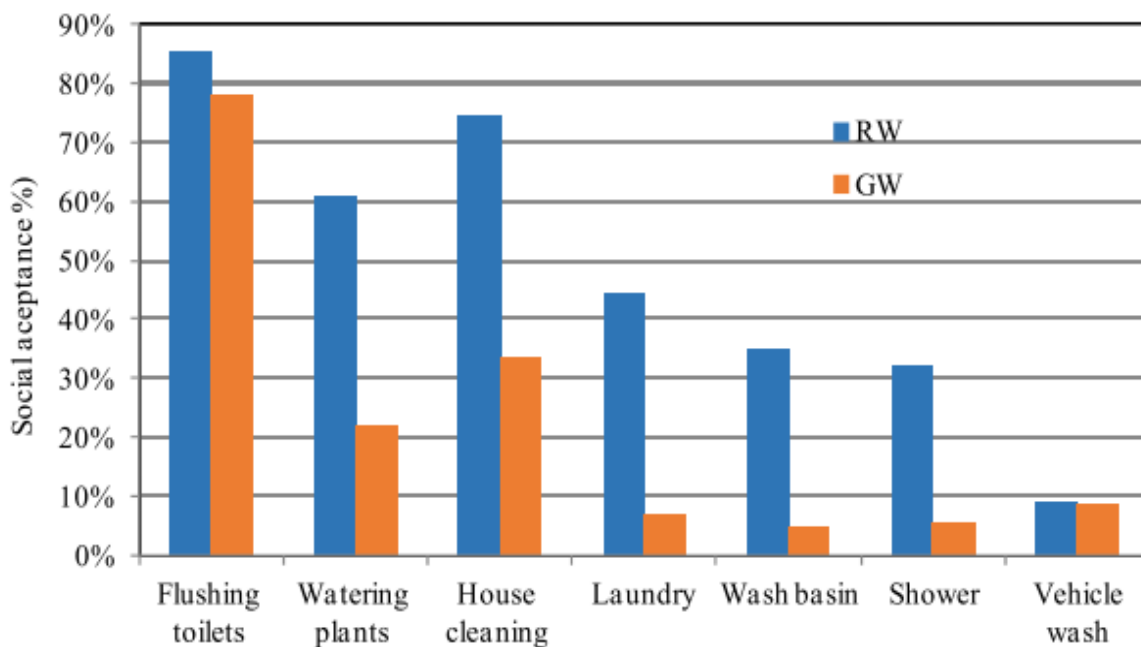


Figure 5: End-user acceptability of rainwater (RW) and greywater (GW) reuse (Dominguez et al., 2017)

It is important to note that, with regards to end-user acceptability, the trends observed through previous research may be significantly different in cases of extreme drought. This is particularly true for cities like Cape Town, South Africa, where citizens were restricted to using 50 litres per person per day (Sunday Times, 2018). Given that this extreme drought has only recently occurred, its impact on the levels of public acceptance regarding rainwater harvesting and greywater reuse have not yet been quantified through published research. However, other studies have shown an increase in

public acceptance, with regards to wastewater reclamation, under extreme drought conditions (Velasquez & Yanful, 2015).

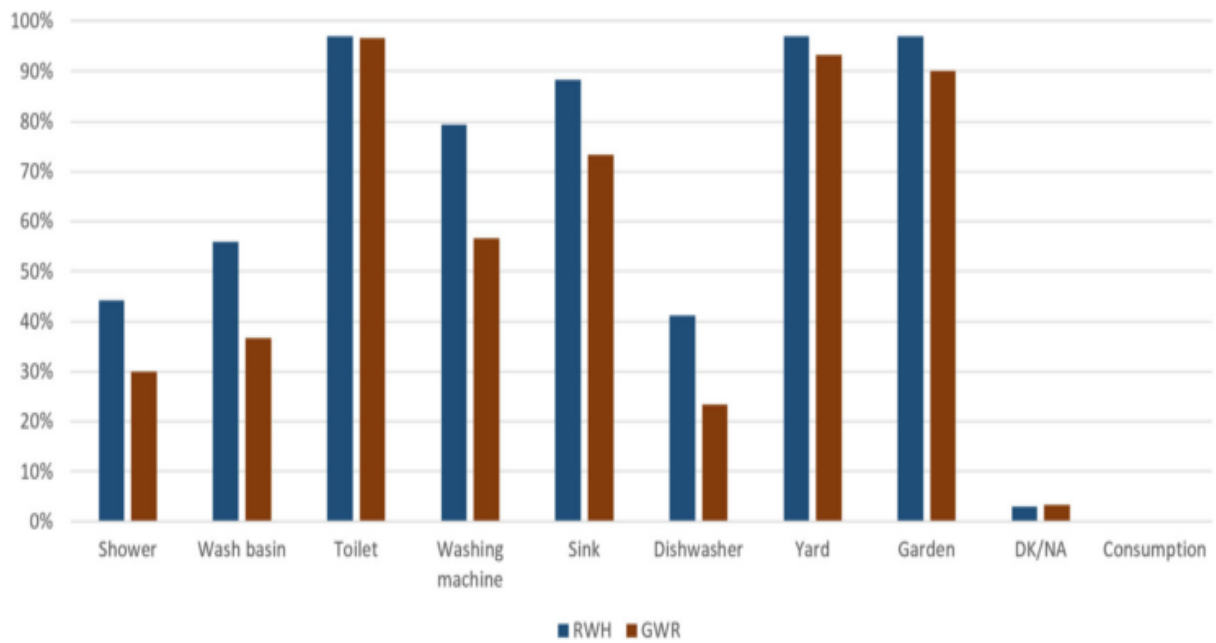


Figure 6: End-user acceptability of rainwater (RWH) and greywater (GWR) reuse (Oviedo-Ocaña et al., 2017)

Table 3: Drawbacks associated with greywater reuse, as indicated by consumers (Domènech & Saurí, 2010)

Dimension	Drawbacks	Respondents (%)
Technical	None	16.7
	Unpleasant odour	60
	Deficient aesthetics of water	13.3
	Breakdowns	16.7
	Improper installation	<1
	Green algae presence	<1
	Staining of the toilet by the colorant	<1
	The difficulties to know whether the system is working properly	<1
	Noise nuisance	<1
Economic	High maintenance cost/maintenance requirements	17.5
	High installation cost	<1
	Room occupied by the machine	<1
Social	Behavioural requirements	3.3
	Children surveillance	<1
Institutional	Very few companies available to carry out the maintenance	<1

2.1.3 Alternative water sources for the CoCT consumer

For the urban CoCT consumer, alternative sources of water within a household containing a low concentration of pollutants, include (i) rainwater collected from the rooftop, (ii) groundwater in the form of wells and boreholes, and (iii) greywater, collected from showers, baths, wash hand basins and laundry facilities. Water produced from these alternative sources may be suitable, with treatment, for indoor use (Zhang et al., 2010). However, given the high cost of accessing groundwater, it is not seen as a solution for all households in Cape Town (Colvin & Saayman, 2007). Also, waste water originating from a household’s kitchen contains a large amount of organic matter (fats and oils) and becomes putrid within a short period of time (Christova-Boal et al., 1996). Hence, it is not considered for greywater production.

The use of alternative water sources, such as rainwater and/or greywater, can offer significant reductions in a consumer’s municipal demand. Considering the distribution of potable water consumption within an urban household, such as in Figure 7 (below), few applications can be seen to require potable water. Furthermore, non-potable applications, such as toilet-flushing, often constitute a large amount of the total household demand. For instance, when considering toilet flushing in a middle to high-income South African Household, shown in Table 4 (below), an average flush frequency of 3 to 4 flushes per person per day is reported, with an average of 15 litres per flush, or approximately 180 litres per day for a middle to high-income household (Van Zyl et al., 2007).

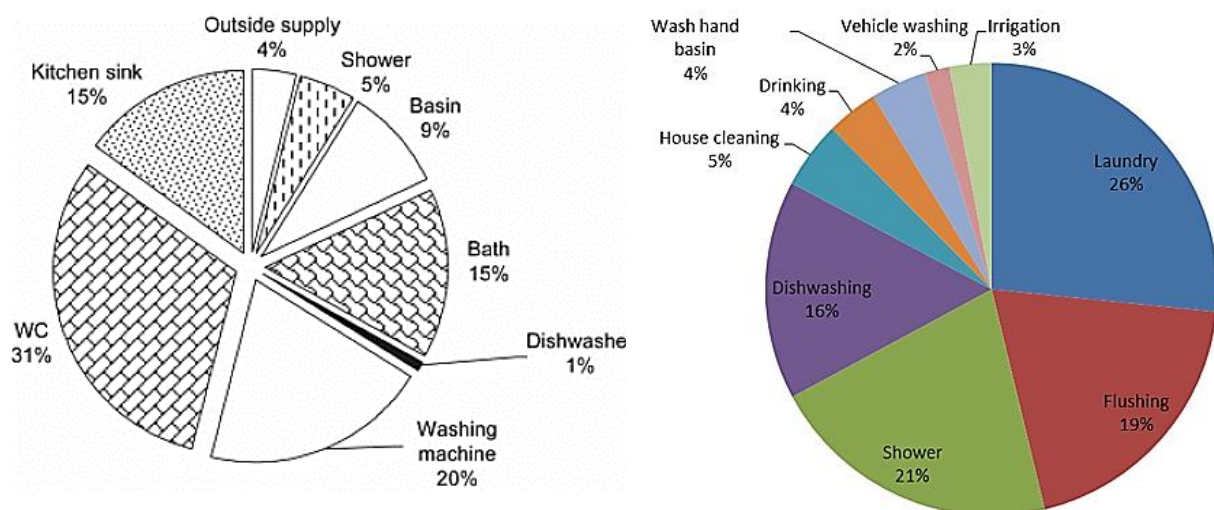


Figure 7: (Left) Distribution of potable water consumption within an urban (industrialised) household (Makropoulos et al., 2008). (Right) Distribution of potable water consumption in Colombian low-income households (Dominguez et al., 2017)

Table 4: Typical end-use patterns for water demand in South Africa (Van Zyl et al., 2007)

Parameter	Value used in model				Units
	High income	Middle income	Township	Informal	
Household size	3	4	6	6	
Bath volume	100	80	50	20	l
Bath frequency	0.6	0.5	0.5	0.7	events/ person/day
Shower volume	80	60	50	40	l/event
Shower frequency	0.6	0.6	0.5	0.3	events/ person/day
Toilet flush frequency	4	3	2.5	2.5	flushes/ person/day
Toilet flush volume	15	15	12	12	l
Clothes washing frequency	0.5	0.3	0.2	0.15	washes/ person/day
Clothes washing volume	120	120	40	40	l
Dishwasher ownership	80	40	5	0	%
Dishwasher volume	30	30	0	0	l/wash
Dishwasher frequency	0.5	0.4	0	0	washes /person/day
Garden irrigation factor	2	0.8	0.2	0	
Crop irrigation factor	As for Kikuyu	As for Kikuyu	As for Kikuyu	0	
Irrigated area	100	40	5	10	m ²
Pool ownership	80	30	0	0	%
Pool cover	30	30	0	0	% of pool owners in mid winter
Pool backwash frequency	0.024	0.024	0	0	backwashes per day
Backwash volume	150	150	0	0	l
On-site leakage returned	6	8	10	10	l/stand/day
On-site leakage not returned	3	4	5	5	l/stand/day
Other volume based demands	30	30	20	20	l/stand/day
Other time based demands	30	30	20	20	l/stand/day
Fraction of volume and time demands returned to sewer	60	60	60	60	%
Cold water temperature	9.7-21.2	9.7-21.2	9.7-21.2	9.7-21.2	°C
Blended water temperature	40	40	40	40	°C

A large percentage of potable water is used in non-potable applications. These applications are seen as producing “recoverable” and “non-recoverable” water. Current non-recoverable uses of potable water, which actually only require non-potable water, include toilet flushing, vehicle washing, laundry, and irrigation. These applications, excluding laundry, lie outside of the greywater stream (i.e. they do not produce greywater). A large percentage of applications currently using (and are more likely to require) potable water also lie within the greywater stream and produce easily recoverable greywater (Rodda et al., 2011). When considering that most individuals find the use of greywater (with little to no treatment) in applications with little human contact acceptable (Oviedo-Ocaña et al., 2017), one can deduce that initial savings in potable water can be significant, when

applying greywater reuse (with little capital investment) within a household for non-potable applications. Research has shown that greywater recycling may result in a reduction of 30% in a household's potable water consumption, whilst rainwater harvesting results in a slightly lower reduction (25%) (Emmerson, 2011; Zhang et al., 2010).

When comparing the applicability of rainwater harvesting, groundwater extraction, and greywater reuse within an urban household, the most appropriate alternative source is greywater (Emmerson, 2011). The reasons for this, based upon literature and the Author's own reasonably founded opinion, are as follows:

- greywater reuse can be undertaken in any household, regardless of its size,
- it can be undertaken almost immediately by any urban household,
- it is an alternative source of water produced daily,
- it is the largest wastewater stream within a household,
- its reuse does not necessarily require the permanent installation of equipment within a household, and
- it may not require significant capital investment, if it is managed in a responsible manner which mitigates associated health risks and is only used in applications with little to no human contact (e.g. Toilet flushing).

2.1.4 Laws and regulations

Although individual (grey) water reuse has been implemented in various countries for several decades, formal standards and guidelines are normally limited to developed countries with a long history of water reuse. The most significant piece of legislation currently applicable in South Africa, for individual water reuse, is the General Authorisations of the National Water Act (NWA) released in 1998 (and revised in 2004) to allow for the reuse of biodegradable effluent for irrigation. Even though greywater is not specifically mentioned in the revision, this piece of legislation is the only document available which can provide (legal) guidance to the South African consumer considering water reuse. Authorisation for greywater reuse, for irrigation, by an individual in a household is given implicitly by Schedule 1 of the NWA (Rodda et al., 2011). Whilst the City of Cape Town has developed water by-laws for water reuse, such by-laws specifically discuss the regulations governing treated sewage and not greywater (City of Cape Town (CoCT), 2009). Internationally reputable guidelines, including the provision of treated greywater quality requirements for reuse, include those of Australia (*Queensland Plumbing and Wastewater Code guidelines*, 2008), America (United States Environmental Protection Agency (EPA), 2012) and Portugal (Sautchuk & al., 2005).

The US EPA requirements for restricted (i.e. controlled) urban water reuse require that treatment include a biological treatment process, such as activated sludge reactors and trickle filters, for the reduction of TSS and BOD below 30mg/l. Disinfection following biological treatment is then required and can only take place once turbidity falls below 5 NTU (measured over a 24-hour period). If turbidity is not used as an indicator, TSS should not exceed 5 mg/l. If membrane filtration is applied following biological treatment and prior to disinfection, turbidity should be less than 0.2 NTU and TSS less than 0.5 mg/l. Disinfection may be carried out using chemical (i.e. Oxidation) or physical (i.e. UV and/or membrane separation) techniques. Disinfected water quality should contain less than 200 CFU (faecal) per 100ml and a minimum residual Chlorine content (if Chlorination is utilised) of 1ppm should be achieved. Treated water quality monitoring must include the measurement of pH (6.0-9.0), TSS, Faecal Coliforms and residual Chlorine (United States Environmental Protection Agency (EPA), 2012).

In 2011, two American National Standards were adopted. These are the NSF/ANSI 350 and NSF/ANSI 350-1, shown in Table 6 (below). These national standards are used to evaluate technologies intended for in-situ treatment and reuse of wastewater, for both commercial and residential purposes (Bruursema, 2011). Standard 350 is most applicable, as NSF/ANSI 350-1 specifically deals with on-site residential and commercial greywater treatment systems for subsurface discharge. The standard NSF/ANSI 350 is applicable to greywater treatment systems for on-site reuse and classifies treated greywater as either being of "Class R" or "Class C". Class R is fit for single-family residences

and Class C is appropriate for multifamily residences and commercial spaces. This standard also provides the (synthetic) influent greywater quality requirements for the testing of the treatment devices (Table 5) and also provides the treated effluent quality requirements (Table 7) that must be achieved with any in-situ treatment device.

Table 5: Synthetic greywater characteristics according to NSF/ANSI 350 (Bruursema, 2011)

Parameter	Required Range
Total suspended solids (TSS)	80–160 mg/L
Five-day biochemical oxygen demand (BOD ₅)	130–180 mg/L
Temperature	25–35°C
pH	6.5–8
Turbidity	50–100 NTU
Total phosphorous - P	1–3 mg/L
Total Kjeldahl nitrogen – N	3–5 mg/L
Chemical oxygen demand	250–400 mg/L
Total organic carbon	50–100 mg/L
Total coliforms	10 ³ –10 ⁴ cfu/100 mL
E. coli	10 ² –10 ³ cfu/100 mL

Table 6: National American Standards NSF/ANSI 350 and NSF/350-1 scope (Bruursema, 2011)

NSF/ANSI Standard 350: On-site Residential and Commercial Water Reuse Treatment Systems	
Building Types	Residential, up to 1,500 gallons per day Commercial, more than 1,500 gallons per day and all capacities of commercial laundry water
Influent Types	Combined black and graywater Graywater Bathing water only Laundry water only
Effluent Uses	Nonpotable applications, such as surface and subsurface irrigation and toilet and urinal flushing
Ratings	Two classifications that vary slightly in effluent quality: <ul style="list-style-type: none"> • Class R: single-family residential • Class C: multifamily and commercial Systems are further described based on the type of influent (combined, graywater, bathing only, laundry only).
NSF/ANSI Standard 350-1: On-site Residential and Commercial Graywater Treatment Systems for Subsurface Discharge	
Building Types	Residential, up to 1,500 gallons per day Commercial, more than 1,500 gallons per day and all capacities of commercial laundry water
Influent Types	Combined black and graywater Graywater Bathing water only Laundry water only
Effluent Uses	Subsurface irrigation only
Ratings	Single effluent quality with no classifications Systems are further described based on the type of influent (graywater, bathing only, laundry only).

Table 7: NSF/ANSI 350 effluent quality criteria (Bruursema, 2011)

Parameter	Class R		Class C	
	Overall test average	Single sample maximum	Overall test average	Single sample maximum
CBOD ₅ (mg/L)	10	25	10	25
TSS (mg/L)	10	30	10	30
Turbidity (NTU)	5	10	2	5
E. coli ² (MPN/100 mL)	14	240	2.2	200
pH (SU)	6–9	NA ¹	6–9	NA
Storage vessel disinfection (mg/L) ³	≥0.5–≤2.5	NA	≥0.5–≤2.5	NA
Color	MR ⁴	NA	MR	NA
Odor	Non-offensive	NA	Non-offensive	NA
Oily film and foam	Non-detectable	Non-detectable	Non-detectable	Non-detectable
Energy consumption	MR	NA	MR	NA

¹ NA = Not applicable

² Calculated as geometric mean

³ As chlorine. Other disinfectants can be used.

⁴ MR = Measured and reported only

The Queensland Plumbing and Wastewater Code guideline used in Australia, as of 2008, was revised to allow for the reuse of treated greywater in toilet flushing, in the washing machine and for vehicle washing. Effluent quality requirements for treated greywater, according to this code, are shown in Table 8 (below). The quality requirements specified by the Queensland government specifically pertain to greywater reuse for indoor use, with high levels of contact expected between the (treated) greywater and the end user. This guideline goes further by specifying design and installation requirements of greywater reuse systems.

Table 8: Effluent quality requirements for greywater reuse (Queensland Plumbing and Wastewater Code guidelines, 2008)

Potential End Use	Parameter	Effluent Compliance Value	Unit
Sanitary flushing Laundry use Vehicle washing External surface wash	BOD ₅	≤10	mg / l
	TSS	≤10	mg / l
	E. Coli ¹	≤1	CFU / 100ml
	pH	6.5-8.5	CFU / 100ml
	Turbidity	<5	NTU
	Residual Cl ²	0.2-1	Ppm

¹ 95% of samples taken over a 12-month period

² If Chlorination applied for primary disinfection. Disinfection may include Ozonation and/or UV irradiation.

The Western Cape Government: Department of Health has also developed a technical memorandum for the implementation of water conservation and water recycling initiatives at state healthcare facilities (Yiannou, 2018). The water quality requirements within this document, shown in Table 9 (below), were based upon requirements stipulated by the Department of Water Affairs and Forestry (1996) South African Water Quality Guidelines (DWA WQG) - Volume 3 - Industrial Use. The technical memorandum assigns water usage as belonging to one of three classes: Class 0, I and II. Each category is then stated as being appropriate for a specific set of domestic and industrial applications. Category 0 is seen fit for human consumption, instrument sterilisation and for high-recycle mechanical plant heating and cooling. Class I is stated as being sufficient for indoor domestic activities, such as bathing, laundry, once-through mechanical plant heating and cooling and for non-forensic pathology services. Class II is seen fit for non-potable, “rough” cleaning applications. This includes surface cleaning, flushing, fire-fighting, washing of vehicles and decontamination areas. As these requirements are defined for state healthcare facilities, additional microbiological constraints were added onto the conventional constraints as described by DWA WQG to ensure complete sterility.

Table 9: Water quality requirements for healthcare facilities. Drinking water excluding radiological and other physical / chemical requirements. Microbiological requirements consider indicator organisms only (Yiannou, 2018)

		Target water quality for healthcare facilities		
Parameter	Unit	Class II	Class I	Class 0
COD	mg O ₂ / Litre	0-75*	0-30*	0-15*
Chloride	mg Cl / Litre	0-900	0-600	0-300
pH	-	4-10	4-10	6.0-9.7
Silica	mg Si / Litre	0-150	0-50	0-20
Sulphate	mg SO ₄ / Litre	0-900*	0-600*	0-250*
Turbidity	NTU	0-15	0-5	0-1
Total Dissolved Solids	mg / Litre	0-2400	0-1800	0-450
Conductivity @ 25°C	mS/m	0-370	0-280	0-70
Total Hardness	mg CaCO ₃ / Litre	0-1000	150-300**	<150
Total Coliform	CFU/100mL	10	10	10
E. Coli	CFU/100mL	0	0	0
Residual Chlorine	ppm (Cl ₂)	1-2	1-2	1-2

*To be re-evaluated if the facility has reported presence of Sulphur Reducing Bacteria (SRB) and Microbiologically Induced Corrosion (MIC).

**For use in laundry, preferable to reduce to <150mgCaCO₃ / l

2.2 Greywater treatment processes

2.2.1 In-situ treatment

Table 10 (below) provides a summary of treatment vs. pollutant removed, to provide non-potable water. To provide potable water, significantly greater levels of filtration, such as Reverse Osmosis, are needed in order to remove dissolved salts and metals (James et al., 2016).

Table 10: Treatment methodologies for pollutant removal in household wastewater streams (James et al., 2016)

Key	
Detergent Characteristics DE – Detergent FO – Foam SU – Surfactant C / BL – Chloride & Bleaches BO – Boron SO – Sodium (incl. compounds) A – Ammonium NI – Nitrates P – Phosphates SE – Sulphates TDS – Total Dissolved Solids O/G – Oil / Grease (attached to surfactant)	Public Perception Characteristics CO – Colour OD – Odour TU – Turbidity TSS – Total Suspended Solids
Physical Treatments	Pollutant
Screening and grit removal	TSS
Dilution	A, P, NI, SU
Storage	FO, TSS
Sedimentation	FO, TSS
Aeration	OD
Floatation	DE, O/G, TSS
Slow Filtration	DE, O/G, TU, TDS, TSS
Rapid Filtration	DE, O/G, TU, TSS
Reverse Osmosis	TDS, SU, BO, SO, SE
Distillation	SU, TDS, SO, SE
Adsorption	SU, BO, OD, CO
Biological Treatments	
Suspended-growth	A, TDS, NI
Fixed-Film reactor	A, TDS, NI
Bio nutrient removal	P, NI
Reed bed	DE, TU, P, TSS, NI
Land Treatment	DE, FO, C/BL, TU, P, TSS, NI
Chemical Treatments	
Coagulation	DE, OD, TU, SU, TSS, BO
Chlorination	OD
Ozonation	SU
Ion exchange	TDS, SU, BO, SO, SE
Electro dialysis	TDS, SO

On-site greywater treatment solutions, for non-potable applications, currently include sand filters, and an array of (fixed and moving) biological reactors with mechanically or gravity assisted aeration, fine membrane filtration technology, purpose built wetlands, photocatalytic technology and chemical treatment processes. Whilst greywater treatment for the purposes of toilet flushing may not be needed (if used within 24 hours), the reduction of its chemical oxygen demand (COD) and total organic carbon (TOC) is necessary if it is to be reused in applications such as (indoor) surface cleaning and laundry. If these pollutants, dissolved and particulate, are not removed, it will result in the scaling of surfaces (for instance by CaCO_3) and the ineffective washing of laundry. Furthermore, if reclaimed greywater is to be used for indoor surfaces, it must be sterile and must not promote microbiological growth (hence the need to reduce COD and TOC, respectively). It should also be noted that some systems which claim to be greywater treatment systems do not actually treat the greywater, but simply divert it into areas where it will be used immediately. Treatment solutions offered can be grouped into three groups, classified as being physical, biological or chemical. Treatment processes often utilise a combination of treatment solutions from each group.

2.2.2 Diversion systems

Greywater has been identified by CoCT as a valuable alternative water source which households are encouraged to make use of, in combination with harvested rainwater. Greywater reuse systems presented in the CoCT information pamphlets make use of a diversion system (City of Cape Town, n.d.). These systems do not treat the greywater, but simply divert the greywater from the collection points to a small holding tank outside of the household, where it is immediately released into the garden by a pump. As the greywater in such systems is untreated, 24-hour storage is prohibited as it may result in a pathogen bloom, posing a serious health risk.

2.2.3 Biological and physical treatment

Typically, greywater reuse including tertiary treatment is seen to become more financially feasible when implemented for several households in a cluster. The Barcelona Metro and the town of Sant Cugat de Valles have implemented local regulations demanding the separation of greywater, to be used for toilet flushing within households. The different kinds of greywater treatment systems and technologies applied in the various households in Sant Cugat del Valles include both basic filtration systems and more complex biological treatment systems, as presented in Figure 8 (Domènech & Saurí, 2010).

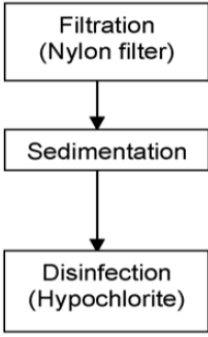
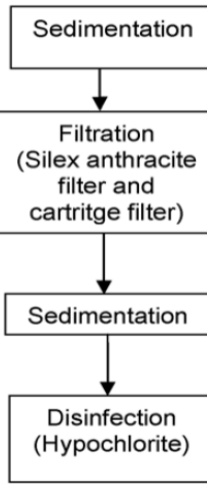
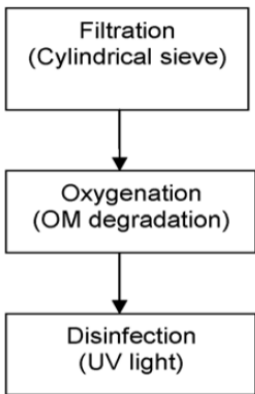
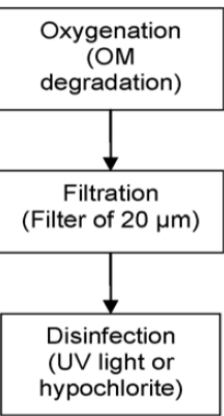
Type of treatment	Type of system			
	Type A	Type B	Type C	Type D
Treatment	Physical	Physical	Biological	Biological
				
Capital cost (€/household)	195	428	1018	691

Figure 8: Technological features of the systems employed in various households of Sant Cugat del Valles (Domènech & Saurí, 2010)

Traditional wastewater treatment takes advantage of the natural respiratory processes within microorganisms, inherent to wastewater containing sewage. However, greywater containing biologically insensitive detergents and disinfectants cannot be treated using conventional biological treatment processes, as these chemicals inhibit the proliferation of the microbiological organisms.

Surendran and Wheatley (2007) designed a bio-filtration device (Figure 9) for the filtration of greywater, to produce water of a near potable quality. The packaged design consisted of four stages including the following treatment techniques: storage, screening, sedimentation, filtration, aeration and further (tertiary) slow gravity driven filtration of increased fineness. The design was reported as being low maintenance and cost effective, producing water of a quality sufficient to meet UK/EU bathing water standards. However, the design is complex, occupies a significant amount of floor space and requires high ceilings if located indoors.

A more recent design, developed by a Chinese/German partnership, is the Membrane Biological Reactor (MBR), which incorporates fine membrane filtration within the aerated chamber utilising biological treatment (James et al., 2016). Whilst it successfully produces water at the qualities stipulated by the UK/EU bathing requirements, the technology is expensive and is energy intensive in its operation.



Figure 9: Greywater treatment plant designed for large institutions (Surendran & Wheatley, 2007)

A pilot study by Atanasova et. al (2017) investigated the use of a MBR for greywater treatment at a hotel in Spain. Economic feasibility of the water treatment system was determined through consideration of CAPEX, OPEX and Payback Period. The complete system included the dual sewerage network, split between black and greywater, MBR technology (illustrated in Figure 10, below), treated water storage and disinfection. The system could exceed treated effluent quality requirements, and is an economically viable solution for buildings producing (i.e. treating) 5 m³ of greywater or more per day (Atanasova et al., 2017). Hence, whilst ideal for small buildings, it is still regarded as being too large and costly for an individual household.

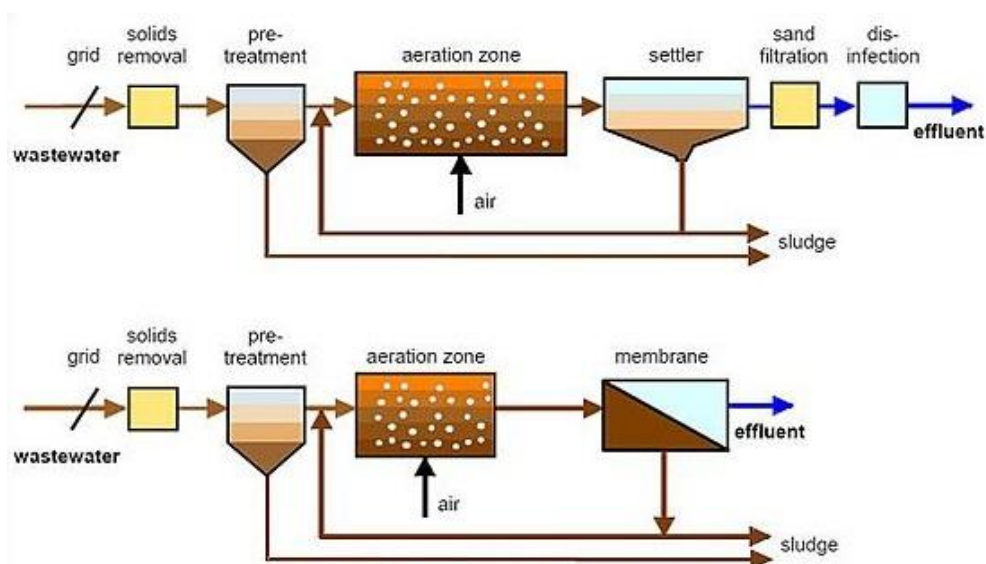


Figure 10: (Above) Activated sludge treatment plant. (Below) MBR treatment process (Yiannou, 2018)

Another technological solution investigated by Chrispim and Nolasco (2017) for the treatment of greywater from several households/sources was the Moving Bed Biofilm Reactor (MBBR), to produce water for non-potable purposes. However, the prototype design was shown to produce treated greywater at a quality sufficient for outside use only and is not suitable for individual households (Chrispim & Nolasco, 2017).

Greywater treatment solutions utilising purpose built wetlands are another option, which allow for an effective system which consumes little energy, is easily maintained, is environmentally friendly and is implemented at little cost. Whilst such a system can be implemented at the household scale, it requires large open spaces (Fowdar et al., 2017). Hence, it may not be regarded as a possible solution for the urban population residing within and around a densely-populated city.

Li et. al (2009) define a greywater reuse standard for non-potable purposes, against which various greywater treatment schemes are evaluated. In their review of literature, it was found that, whilst greywater has sufficient biodegradability, the COD:N:P ratio may not be balanced, depending upon the source of the greywater. Thus, biological treatment alone is not sufficient to reduce the organic, nutrient and surfactant content to an acceptable level for use in urban buildings. Additional tertiary treatment processes are often required.

2.2.4 Chemical treatment

Tsoumachidou et. al (2016) investigated the use of photocatalytic technology for the treatment of greywater. The performance of a Pyrex reactor and a slurry fountain photo reactor were evaluated whilst considering the dependence of the process efficiency on catalyst concentration, Fe(III) concentration, pH and incident radiation (Tsoumachidou et al., 2017). Whilst significant reductions in organic matter can be achieved with such technology, it is not a solution adopted universally for greywater treatment. Application of such technology is site specific and far too complex and expensive to be considered for a single household.

Gassie and Englehardt (2017) also evaluated the performance of photocatalytic technology making use of an advanced oxidation and disinfection process for in-situ greywater treatment and reuse. The performance of the technology was measured against treated water quality, energy demand, environmental impact and operational simplicity (Gassie & Englehardt, 2017). Whilst the technology proves to be promising, it is complex, energy intensive and expensive. Hence, it is not able to treat greywater within the socio-economic constraints of an urban setting.

Other chemical solutions for the treatment of greywater for reuse have also been researched, including the use of coagulants, flocculants and magnetic ion exchange. However, these solutions

were found to only be effective for low-strength greywater sources; a combination of biological treatment and physical filtration, followed by disinfection, was found to be the most effective for the treatment of greywater for reuse (Li et al., 2009; Pidou et al., 2008).

2.3 Technological requirements for the urban consumer

2.3.1 Solutions for the urban CoCT consumer

Several authors have focused their research on the treatment of greywater produced using conventional detergents and disinfectants. No consideration is given regarding the treatment process and technology needed to obtain treated effluent at the required quality, if the products used in the greywater stream are changed and specific biologically insensitive pollutants removed from the start. For instance, if biodegradable detergents are used by the consumer, biological processes will be far more efficient in providing the necessary treatment (Henze et al., 2008). Furthermore, disinfection of the water, after it has received treatment through a biological process, will ensure sufficient sterilisation of the water without detracting from the performance of the biological treatment process.

Hence, in light of the literature presented above, it is evident that a combination of biological and physical treatment processes, such as an activated sludge reactor followed by tertiary filtration and disinfection, are considered to be the most appropriate means for in-situ greywater treatment and reuse (Li et al., 2009) by the urban consumer. Disinfection may also be performed manually, by the user, as and when required (for instance through chlorination), as this will reduce the complexity of the technology needed, whilst significantly reducing any health risks. Thus, a review of technologies commercially available to the consumer, considering the above, was performed.

2.3.2 Methods for the evaluation of existing technologies

From the preceding literature, it is evident that technological constraints are both qualitative and quantitative. Qualitative requirements include the level of perceived complexity by the end user, along with the aesthetics of the technological solution offered. However, given that design aesthetics can severely limit any design, it will not be considered for the purposes of this dissertation. Hence, only the perceived complexity will be considered qualitatively.

The study undertaken by Domenech et. al (2010) paid close attention to the socio-technical constraints determining public acceptance of greywater reuse technologies. In their study, a level of acceptance of greywater reuse, for toilet flushing, was obtained through a survey of several households currently employing greywater reuse systems for toilet flushing. The factors that were identified in their study, shown in Table 11 (below), were incorporated into a linear regression

model (equation 1) to examine their influence on public acceptance levels. Each factor was measured by using at least one indicator. A is defined as the level of public acceptance, HR as the perceived health risk, OR as the operating routine, C as the perceived cost, EA as their level of environmental awareness and ε as the regression analysis error. The author concluded that the most significant drawbacks regarding greywater reuse include unpleasant odours, followed by aesthetics, reliability and cost.

$$A = \beta_0 + \beta_1 HR + \beta_2 OR + \beta_3 C + \beta_4 EA + \varepsilon \quad (1)$$

In the study performed by Dominguez et. al (2017), the perception that low income households would place greater importance on cost and economic benefits of rainwater harvesting and greywater reuse systems was proven to be false. Instead, greater importance was placed on the volume of water that could be saved. Financial feasibility was determined using equation 2 below, where PP is the payback period, n_y is the number of years following investment at which the last negative value of cumulative cash flow occurs, n is the value of cumulative cash flow at which the last negative value of cumulative cash flow occurs and p is the value of cash flow at which the first positive value of cumulative cash flow occurs.

$$PP = 1 + n_y - \frac{n}{p} \quad (2)$$

Whilst the calculation of payback period is simple and regularly applied in investment decisions, a more reliable means of deciding whether or not to proceed with an investment is to calculate Net Present Value (Jan, 2013). In equation 3, R_t is the expected net cash inflow for year t , i the discount rate (dictated by the rate of inflation) per year, N the number of years the treatment device operates, and t the period in which the cash flow is received.

$$NPV(i, N) = \sum_{t=0}^N \frac{R_t}{(1+i)^t} \quad (3)$$

Table 11: Indicators used in determining public acceptance level of greywater reuse systems (Domènech & Saurí, 2010)

Variable	Indicators	Index
Acceptance	What did you think when you got to know that your toilet functions with greywater?	1 = Very positive (...) 5 = Very negative
	Are you satisfied with your greywater reuse system?	1 = Very satisfied (...) 5 = Very unsatisfied
	Would you recommend to a friend to install a greywater reuse system?	1 = Yes 3 = Indifferent 5 = No
Perceived Health Risk	How do you perceive the risks to human health associated with greywater reuse?	1 = Very low (...) 5 = Not high
Perceived Cost	How do you perceive the costs associated with having a greywater reuse system?	1 = Very low (...) 5 = Very high
	How important do you consider any economic savings to be?	1 = Very Important (...) 5 = Unimportant
Operating Routine	Is your system working properly?	1 = Yes 3 = Indifferent 5 = No
	How often do you suffer from disruptions of the service?	1 = Never (...) 5 = Very often
	How often do you suffer from unpleasant smells?	1 = Never (...) 5 = Always
Environmental Awareness	Do you agree with the following statement? "I am an environmentally responsible person"	1 = Strongly agree (...) 5 = Strongly disagree
	What kind of waste do you recycle?	1 = Everything (...) 5 = Nothing
	How important do you consider the benefit of water saving to be?	1 = Very Important (...) 5 = Unimportant

2.4 Existing commercial technologies

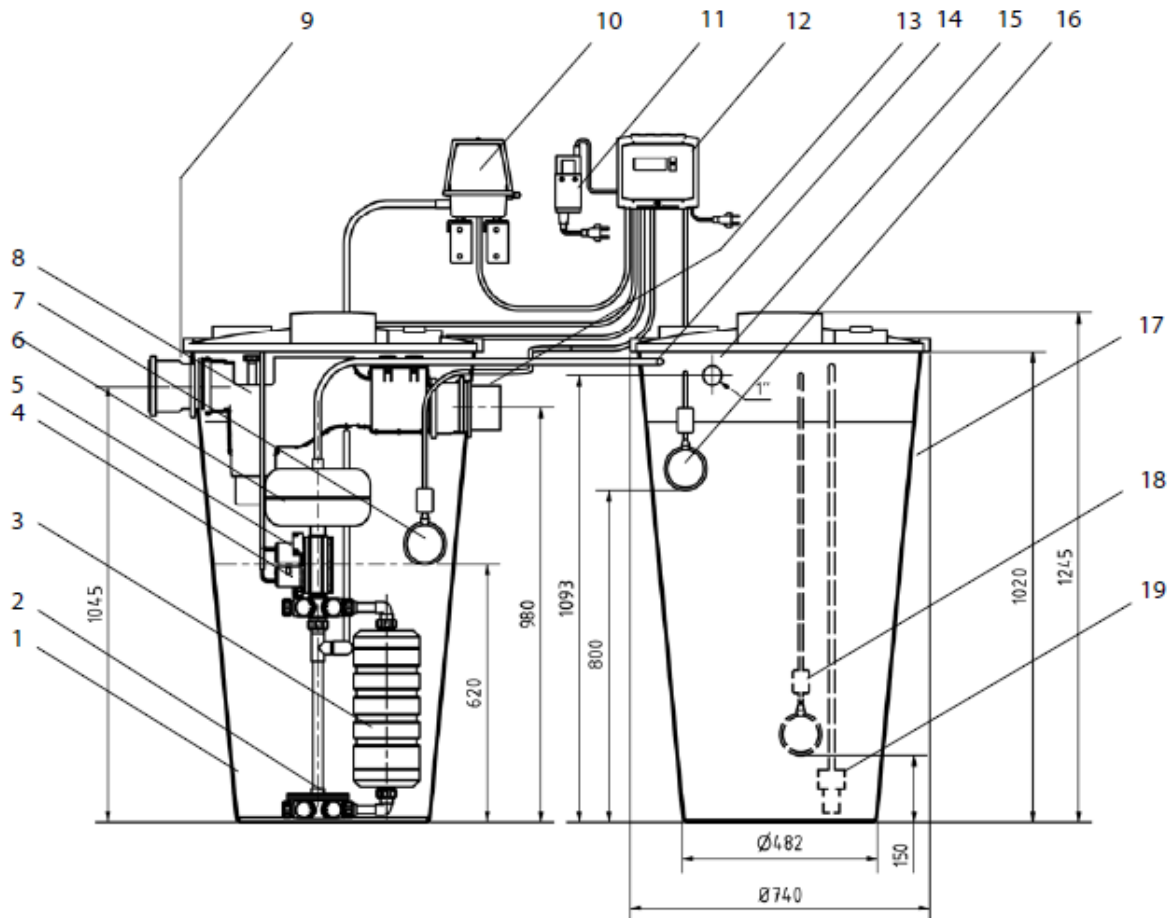
Technologies and treatment processes considered appropriate were biological and physical, suitable for treating greywater produced through the use of predominantly biodegradable cleaning products. Greywater diversion systems were not considered, as these do not treat the greywater influent, but simply divert raw greywater to irrigation systems. The treatment capacity of existing commercial technologies considered for this study was limited to approximately 4 person equivalents per day (i.e. a single household), with a maximum water demand of 130 litres per person per day, as indicated in Table 1 for a “moderate to high” developmental level. Based upon preceding literature, approximately 50 to 65% of a household’s water demand is used in the production of greywater, thus producing approximately 65 to 85 litres of greywater per person per day. However, a “moderate” developmental level may also be seen as more representative for cities experiencing extreme drought. For instance, the City of Cape Town had restricted residents to 50 litres per person per day due to extreme drought conditions (Sunday Times, 2018).

Product information required for the evaluation of existing technologies was obtained through literature and product data which is freely available to the consumer (unless indicated otherwise). Where sufficient information on technologies was not available, suppliers were contacted to obtain the necessary (non-proprietary) information.

2.4.1 AQUALOOP 300

The AQUALOOP 300 (shown in Figure 11, below) is described as a modular greywater treatment system, utilising a three step treatment process. It is robust enough to deal with “shock” loads³ and to receive raw greywater with varying amounts of pollution (BOD<200mgO/l). The daily treatment capacity of the AQUALOOP 300 is 300 litres per day (Pure Rain Technologies Pty Ltd, 2017), producing treated greywater which meets the quality requirements as specified by NSF/ANSI 350-2014, shown in Table 12 (below).

³ The receiving of large volumes of raw greywater within a short space of time



1. Bioreactor	11. 24 Volt switching power supply
2. Wheel weight	12. Control unit
3. Membrane	13. Bioreactor emergency overflow
4. Suction pump	14. Clear water inflow
5. Back flush pump	15. Clear water tank emergency overflow
6. Float switch Bioreactor BR min	16. Float switch clear water CL max
7. Back flush tank	17. Clear water tank
8. Pre-filter	18. Float switch clear water min (e.g. RM Eco)
9. Bioreactor inflow	19. Clear water suction
10. Blower	

Figure 11: AQUALOOP 300 Greywater Treatment System (INTEWA GmbH, 2017b)

The design makes use of two tanks. The receiving tank (i.e. the bioreactor) makes use of a clear sieve filter, through which the raw greywater passes before entering the bioreactor. This filter is used to remove lint, hair and other large particulates. Within the bioreactor, growth media (shown in Figure 12, below) are inserted. The growth media consists of small plastic elements, which increases the surface area to which the bacteria can attach. It is these bacteria, like in the conventional municipal sewage treatment process, that are responsible for the (aerobic) biological treatment of the greywater (Pure Rain Technologies Pty Ltd, 2017).



Figure 12: AQUALOOP 300 growth bodies (INTEWA GmbH, 2017a)

An ultra-fine membrane station (0.2 microns), controller and air blower is also provided in the bioreactor and is shown in Figure 13 (below). The design allows for the simultaneous aeration and cleaning of the membrane filters, prolonging their service life with minimal maintenance (Pure Rain Technologies Pty Ltd, 2017).

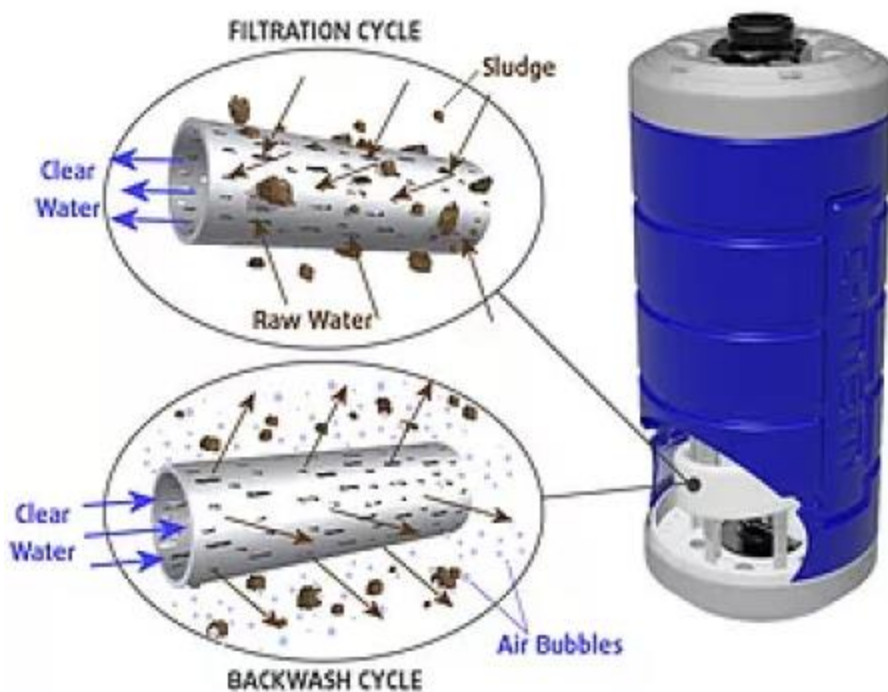


Figure 13: The two modes of operation for the AQUALOOP 300 membrane station (Pure Rain Technologies Pty Ltd, 2017)

After the treated greywater is extracted through the membrane filter, it is deposited into the clear water tank. Level switches, together with a submersible pump, are used to feed the treated water back into the household reticulation network. The treated water quality is fit for irrigation, household cleaning (including laundry), the topping up of pools and for toilet flushing (Pure Rain Technologies Pty Ltd, 2017).

The unit is automatic in its operation and typically requires no human intervention. However, it is recommended that the filter basket be cleaned (manually) every 3 to 4 months. Energy consumption

costs are estimated at 1.4kWh / m³. The AQUALOOP 300 can be purchased locally for R65 000 (excl. VAT).

Table 12: Water quality test results following treatment of greywater by the AQUALOOP 300 (INTEWA GmbH, 2016)

Requirement and approval results of effluent quality according to NSF/ANSI 350-2014

	Influent range source water ⁴	Requirement effluent NSF/ANSI 350-2014 Class C		AQUALOOP effluent Test results NSF approval Class C	
		Test Average	Single Sample Maximum	Result Average	Single Sample Maximum
CBOD ₅	130 – 180 mg/l	--	--	--	--
BOD ₅	--	10 mg/l	25 mg/l	5 mg/l	17 mg/l
TSS	80-100 mg/l	10 mg/l	30 mg/l	2 mg/l	7,8 mg/l
turbidity (NTU)	50-100 NTU	2 NTU	5 NTU	0.57 NTU	3.89 NTU
E. coli ²	10 ² -10 ⁴ cfu/100ml	2.2 MPN/100ml	200 MPN/100ml	1.0 MPN/100ml	13.0(MPN/100ml
pH	6.5 – 8.0	6.0 – 9.0	NA ¹	7.38	NA ¹
total phosphorous - P	1.0 -3.0 mg/l	--	--	--	--
total Kjeldahl nitrogen-N	3.0 – 5.0 mg/l	--	--	--	--
color	--	MR ³	NA	MR ³	NA
odor	--	Non offensive	NA	Non offensive	NA
oily film and foam	--	Non-detectable	Non-detectable	Non-detectable	Non-detectable

¹ NA: not applicable.

² Calculated as geometric mean.

³ MR: measured and reported only.

⁴ System for treating bathing and laundry source waters (combined)

2.4.2 Aqua2Use GWTS 500

The Aqua2Use GWTS 500, illustrated in Figure 14 and Figure 15 (below), receives raw greywater from the various greywater sources in a pre-filtration tank. This tank contains several screens which remove hair, grit, lint, soap scum and silt. The concentration of total suspended solids (TSS) is said to be reduced by 60% to 90%. The pre-screened greywater is then pumped from the pre-filtration tank into a biological treatment tank which makes use of the activated sludge treatment process and dissolved air flotation. In this chamber floating scum is skimmed off of the surface using a “floating” skimmer. Sludge is rejected through the bottom of the conical section (Matala Water Technology Co. Ltd., 2010).

A dissolved air flotation pump is then used to transport the activated greywater into a second sedimentation tank, such that organic particulates (i.e. settleable biomass) which have accumulated as a result of the activated sludge treatment process can be removed through settling. The clarified activated greywater then overflows through a communication pipe at the top of this (second) chamber, into a third chamber. In the third chamber the activated sludge treatment process continuous, with the addition of Matala[®] filtration media providing additional surface area for biological treatment (Matala Water Technology Co. Ltd., 2010). Following the second biological

treatment stage, the water is extracted and passed through a (broad-based irradiation) UV-C disinfection chamber. The quality of the water produced, shown in Table 13 (below), is fit for laundry, surface cleaning, toilet flushing and irrigation (Matala Water Technology Co. Ltd., 2010).

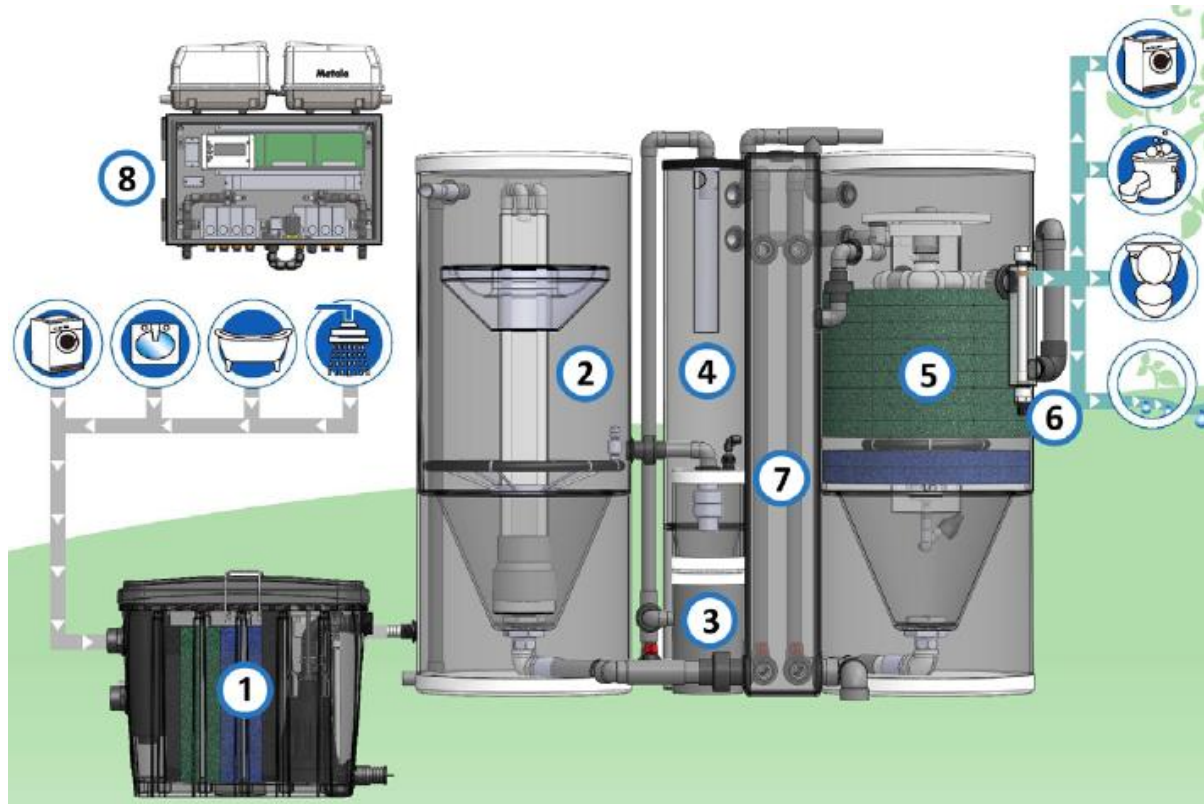


Figure 14: Illustration of the Aqua2Use GWTS 500. (1) Progressive Depth Filtration (2) Buffer Chamber/Active Sludge Treatment/Skimming (3) Air water pump (4) 2nd Sedimentation process (5) Biological treatment using progressive biofiltration (6) UV Disinfection (7) Drainage and purging chamber (8) Control Panel (Matala Water Technology Co. Ltd., 2010)

The Aqua2Use GWTS 500 is automatic in its operation and generally does not require human intervention. Its treatment capacity is 500L per day. Maintenance of the unit is typically performed (manually) every 12 months. This includes the cleaning of air filters for the two air pumps and the replacement of the UV lamp. Every 24 months it is recommended that the diaphragms of the two air blowers be replaced. Annually, this equates to less than \$100 USD. The Aqua2Use GWTS 500 is not available locally and costs approximately \$8 100 USD to purchase (excluding taxes and import duties) (Aqua2use, 2010).

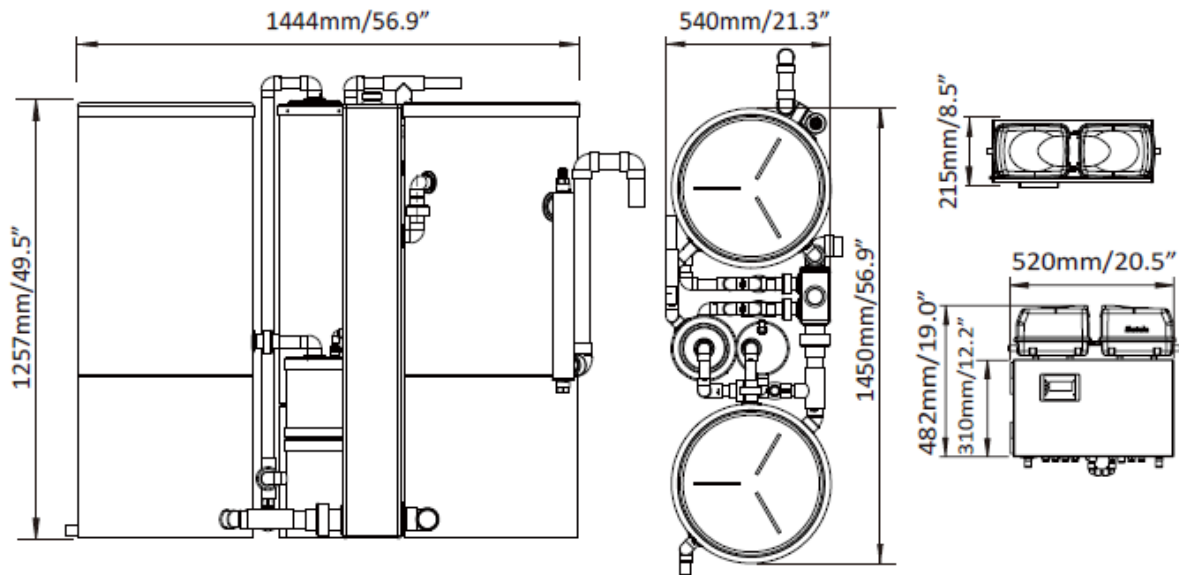


Figure 15: Schematic drawing of the Aqua2Use GWTS 500 (Matala Water Technology Co. Ltd., 2010)

Table 13: Water quality test results following treatment of greywater by the Aqua2Use GWTS 1200 treating 1200 L/d. Effluent quality is expected to be the same across all models (such as the GWTS 500) (Aqua2use, 2010)

Certification Test Results of Aqua2use® Greywater Treatment System
NATA-approved lab water tests over a period of 6 months with 31 samplings total

		BOD	SS	E.Coli	Turbidity	pH	Conduct.
		mg/L	mg/L	Orgs/100ml	NTU	pH units	uS/cm
AU Standard	Indoor use	<10	<10	<10	n.a.	n.a.	n.a.
	QLD Class A	20	5	<10	<2 (5)	6-8.5	1600
"Aqua2use® Effluent"	average	<3	<2	<1	0.47	7.9	497
	max	<3	5	<1	0.9	8.2	728
	min	<3	<2	<1	0.3	7.6	324
"Aqua2use® Influent"	max	666	110	220000	268	9.8	856
	min	36	26	160	30	7.04	244

Flow rate 900 LPD(243GPD)
 Test performed with GWTS1200
 Water sampling and analysis done by:
 Moreton Bay Water Scientific Services Caboolture District, Australia
 NATA Accreditation no. 14476

2.4.3 RECOVER Greywater Treatment System

The RECOVER Greywater Treatment System®, shown in Figure 16 (below), is designed to collect greywater harvested from showers, baths, wash hand basins (excl. kitchen sinks) and laundry machines. The treatment system receives, filters and treats the greywater in a single vessel (Bio-Microbics Inc., 2018).

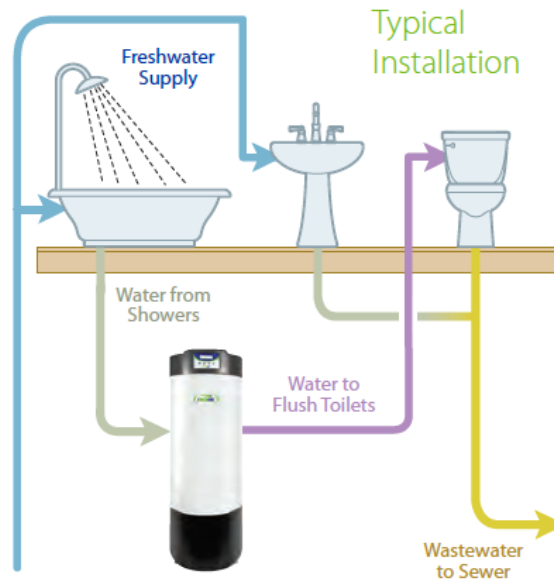


Figure 16: Illustration of greywater reuse using the RECOVER Greywater Treatment System (Bio-Microbics Inc., 2018)

The greywater is directed into the vessel, where it is passed through a self-cleaning CleanScreen® filter, shown in Figure 17 (below). The filter is designed in such a way as to avoid the need for regular human intervention for its cleaning and maintenance (Bio-Microbics Inc., 2018). An inline strainer is also provided upstream of the (treated) greywater pump, for redundancy.

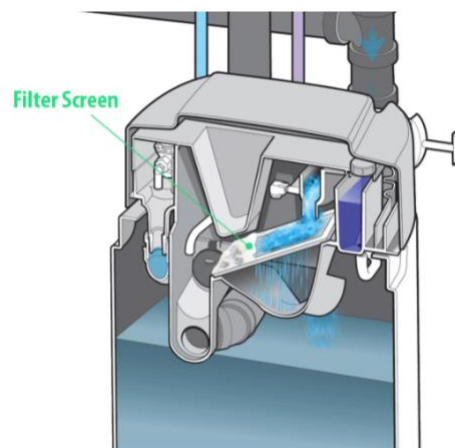


Figure 17: The RECOVER Greywater Treatment System self-cleaning CleanScreen Filtration process (Bio-Microbics Inc., 2018)

After passing through the CleanScreen® filtration process, the greywater is stored in the vessel for chlorination. The chlorination process is automatic, with the amount of chlorination dependent upon the volume of greywater received by the treatment system. The chlorinator (shown in Figure 18, below) makes use of pool tablets, which typically last up to 6 months. The treated water produced by the RECOVER® Greywater Treatment System is fit for toilet flushing (Bio-Microbics Inc., 2018).

The treatment capacity for the RECOVER® Greywater system is 200L per day. Maintenance is typically performed on an annual basis, the cost of which (including consumables) equates to less than \$10 USD per year. The RECOVER® Greywater Treatment System can be purchased for \$3395 (excl. taxes and import duties) and is not available locally.

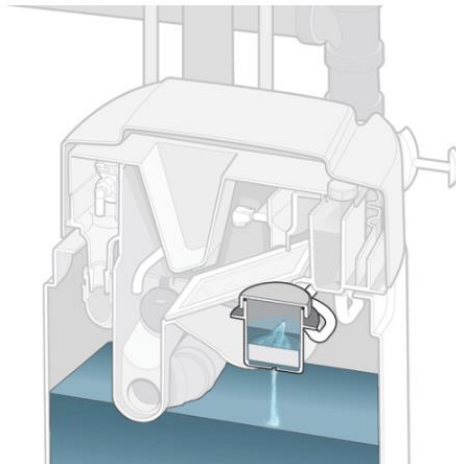


Figure 18: The RECOVER Greywater Treatment System chlorination process (Bio-Microbics Inc., 2018)

2.4.4 HYDRALOOP R

The HYDRALOOP greywater treatment unit shown in Figure 19 (below) is designed to receive, treat and store water from baths, showers and washing machines. The treatment unit, unlike other treatment systems, does not make use of any filtration devices. This is done to avoid the need for regular manual cleaning, ultimately limiting direct human contact with the (untreated) greywater. The unit is also designed to allow for automatic cleansing, without the need for any human intervention. The unit is self-regulating, with several safety systems incorporated to monitor system performance (Hydraloop, 2018a).

The treatment unit makes use of 6 treatment processes for the removal of soaps, dirt and particulates (dissolved and suspended). These processes include (in the following sequence) sedimentation, conventional floatation, Dissolved Air Flotation (DAF), skimming and aerobic digestion. The device operates in a way that allows for “self-cleaning” through the DAF process and skimming, wasting lint and other particulates to the sanitary drain when necessary. The final treatment process utilises a UV light for disinfection, after which the treated greywater is stored (Hydraloop, 2018a).

The HYDRALOOP greywater treatment unit is capable of producing water of a quality which meets the BS8525 and NSF/ANSI-350 international standards and is summarized in Table 14 (below). Treated greywater may be used for toilet flushing, irrigation and laundry. The total treatment capacity is rated at 440 Litres per day (Hydraloop, 2018b). Total energy consumption equates to

approximately 110kWh per annum. The HYDRALOOP greywater treatment unit is currently not available locally. However, the company does plan to expand into the South African market. The purchase price (excluding taxes and import duties) is 2995.00 Euros.

Table 14: Water quality of treated greywater produced by HYDRALOOP R (Hydraloop, 2018a)

Parameter	Unit	Treated Water Quality
BOD ₅	mg/L	<10
TSS	Mg/L	<10
Turbidity	NTU	<5
E. Coli	CFU/100mL	<1
pH	-	6.0-9.0

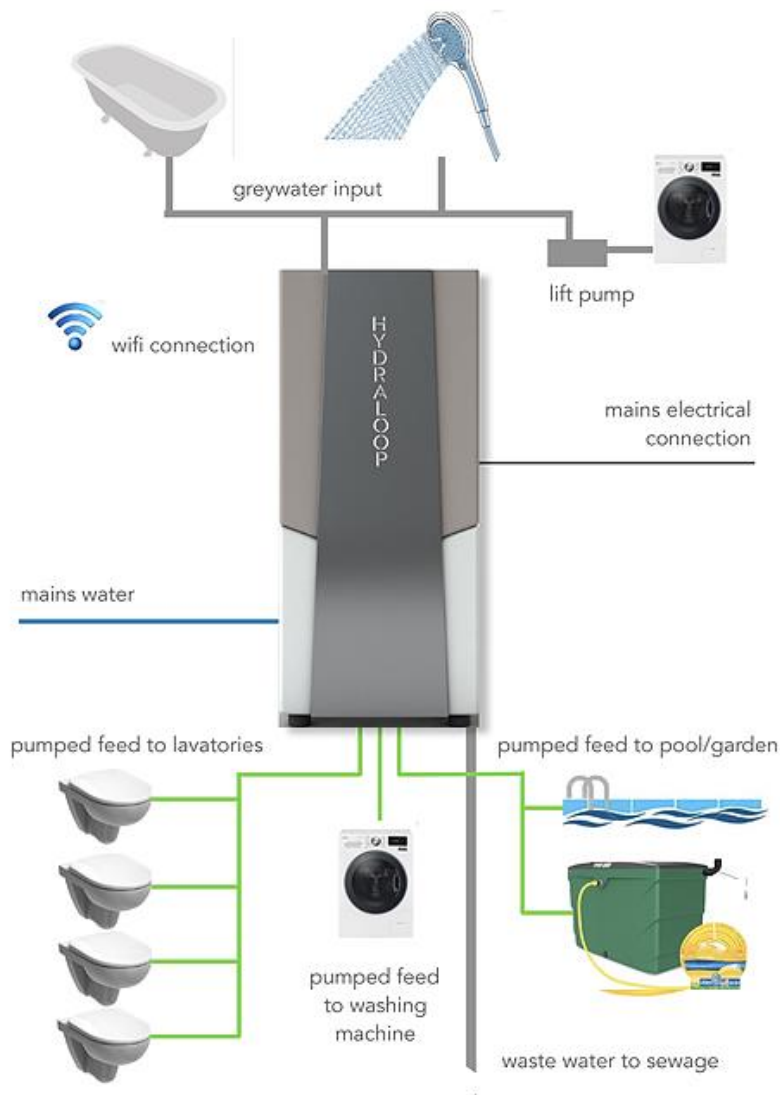


Figure 19: Illustration showing how the HYDRALOOP R is incorporated into a household's reticulation network (Hydraloop, 2018a)

3. Methods

3.1 Defining an illustrative urban household

As shown in Figure 4 of the preceding literature study, apartments, complexes and houses consume the largest amount of water and thus produce the most greywater. Hence, for the purposes of this study, the “illustrative household” was defined as a middle-income household with a piped water supply to a house or apartment. A description of the socio-economic characteristics defining this illustrative household is given in Table 15 (below), with the “Restricted” demand representing the household’s water consumption under drought conditions.

Table 15: Parameters used in this study to define an “illustrative” middle-income household in the City of Cape Town, based upon preceding literature

Parameter	Characteristic	Source
Alternative water source	Greywater	Section 2.1.3
Household income bracket	R4 217.83 - R33 741.75 / month	(City of Cape Town, 2016)
Property type	flatlets, apartments, houses	Section 2.1.1
Property tenure	Rented (i.e. no ownership)	Section 2.1.1
Occupants	2 to 4	
Typical specific water demand	169 Litres / person per day ⁴	Section 2.1.3 - Table 4
Restricted specific water demand	48 to 98 Litres / person per day	Section 2.1.1 - Table 1
Typical specific greywater production	111 Litres / person per day ⁵	Section 2.1.3 - Table 4
Restricted specific greywater prod.	31 to 64 Litres / person per day ⁵	See Footnote 5
Accessibility to municipal water	Piped into property	
Property electrification	Yes	

3.2 Evaluation of existing technologies

3.2.1 Treated water quality

Existing technologies capable of producing treated greywater would be considered, the quality of which was to be evaluated against that specified in Table 16 (below), which is *only fit for toilet flushing⁶, clothes washing and surface cleaning*.

⁴ Figure obtained when considering a middle-income household (Table 4) which does not have a swimming pool and is not able to irrigate their garden due to water restrictions (City of Cape Town, 2018a).

⁵ Based upon Table 4, excluding wastewater from a dishwasher, and considering an ENERGY STAR-rated washing machine with a residual moisture content of 50% (B&C TECHNOLOGIES COMMERCIAL LAUNDRY BLOG, 2014; Coolblue N.V., 2019; Whirlpool, 2019). This equates to 66% of the specific water demand.

⁶ Untreated greywater is suitable for toilet flushing, provided it is used within 24 hours from generation.

Table 16: Water quality targets defined for the purposes of this thesis for greywater reuse (the limits of which are informed by various sources as discussed in the Literature Review)

Potential End Use	Parameter	Effluent Compliance Value	Unit
Sanitary flushing Laundry use Vehicle washing External surface wash	COD (or BOD ₅) ⁷	≤30 (≤15)	mg O ₂ / l
	TSS	≤10	mg / l
	E. Coli ⁸	<1	CFU / 100ml
	Turbidity	<5	NTU
	pH	6.0-9.0	-

3.2.2 End user acceptability

To predict an existing technology's end-user-acceptability, A , the dimensions as described in Table 17 (below) are used. Equation 4 is used to calculate the technology's acceptability score. A specific weighting is assigned to each dimension, using a total of 4 dimensions as defined (in Table 3) by Domènech et al (2010). The effluent quality is also taken into account in the prediction of an existing technology's end-user-acceptability.

$$A = \frac{w_o + \beta}{2} \quad (4)$$

Where

$$\beta = w_1 \cdot (\text{Tech Score}) + w_2 \cdot (\text{Economic Score}) + w_3 \cdot (\text{Social Score}) + w_4 \cdot (\text{Inst Score}) \quad (5)$$

For the calculation of each dimension score (e.g. Technical Score), the score of each drawback considered for a particular dimension is multiplied by the drawback weighting factor. All weighted drawback scores, for the dimension in question, are summated to provide the unweighted dimension score, which is then multiplied by the dimension's assigned weighting factor.

The dimensional weighting factors, w_x , were decided by considering the significance of the various drawbacks of greywater reuse technologies as stated in Table 3. For example, 60 percent of respondents experienced drawbacks relating to the technical aspects of greywater reuse technologies. Hence, a weighting factor of 60% was assigned to the technical dimension. Similarly, a small percentage of respondents in the study by Domènech et al (2010) experienced drawbacks associated with the social and institutional dimension (approximately 3% and 1%, respectively). Hence, the social and institutional dimensions in the acceptability calculation above were also assigned a dimensional weighting of 3% and 1%, respectively. The remaining (economic) dimension was assigned with a weighting factor of 36%, so that all dimensions combined achieve unity.

⁷ Using an approximate ratio of COD \approx 2BOD₅ where wastewater properties are unavailable

⁸ Specifying an E. Coli count < 1 CFU/mL, as opposed to the NSF/ANSI350 of <14 CFU/100mL, will result in a lower perceived health risk (i.e. "yuck" factor)

The drawbacks associated with the economic and institutional dimensions were assigned equal drawback weighting factors as they were regarded as being equally important.

Considering that the extreme drought experienced by households in the City of Cape Town was a relatively recent occurrence, data concerning perceived drawbacks associated with the technical, economic, social and institutional dimensions specific to a household in Cape Town does not yet exist. However, research undertaken by Velasquez et al (2015) showed that, under drought conditions, consumers are more accepting of the idea of using reclaimed wastewater to meet their domestic needs. Thus, when considering the impact of drought conditions on the perceived drawbacks associated with greywater reuse in households in the City of Cape Town, it is reasonable to assume that households are more willing to change their behaviour and attenuate their acceptance criteria relating to the use of treated greywater under drought conditions. To account for these characteristics of the “illustrative household” in the City of Cape Town, the drawback weighting factors concerned with the technical and social dimensions were selected in a way that allows for (i) a greater tolerance of treated water which may be deficient in aesthetics, and (ii) a greater tolerance for technological solutions which require behavioural change.

In Equation 4, w_o is determined in accordance with the treated water quality achieved. For every compliance value achieved, a unit value is considered towards the value of w_o . The total number of units obtained is then divided by five for normalisation, yielding w_o . The acceptability value, A , is then multiplied by 100 when expressed as a percentage.

3.2.3 Financial feasibility

An economic feasibility analysis was performed for each technology, by determining the Net Present Value (Equation 3), and any savings in municipal water were considered as a positive cash flow over the life of the treatment device. A positive Net Present Value (NPV) indicates that the capital which is spent on the treatment device is recuperated over its lifetime. Conversely, a negative NPV indicates that the capital investment is not recuperated.

Table 17: Dimensions, drawbacks and weighting factors assigned for the prediction of an existing technology's end-user-acceptability, in the context of the urban CoCT household.

Dimension	Dim. Weight, w_x	Drawback weight	Drawbacks	Index Guide
Technical	0.6	0.225	Unpleasant odour	1 = rarely 0 = regularly
		0.1	Deficient aesthetics of water	1 = rarely 0 = regularly
		0.225	Floor Space	1 if < 1 m ² 0 if > 1m ²
		0.225	Device mobility	1 = Portable 0 = Fixed
		0.225	Complexity	1 = simple ⁹ 0 = complex ⁹
Economic	0.36	0.5	Monthly running costs (incl. replacement cost)	1 = less than 0.5% of monthly household income 0 = greater than 0.5% of monthly household income
		0.5	Purchase Price	1 if < 50% monthly salary 0 if > 50% monthly salary
Social	0.03	0.4	Behavioural requirements	1 = Little to no behavioral change needed 0 = Major behavioural change needed
		0.6	Children surveillance	1 = Little to no behavioral change needed 0 = Major behavioural change needed
Institutional	0.01	1	Availability of local technical support ¹⁰	1 = Local technical support readily available 0 = Local technical support not available

⁹ If treatment device contains more than 2 electro-mechanical components, it is regarded as being a complex design.

¹⁰ i.e. Within South Africa

3.3 Prototype Design

3.3.1 Design parameters

The design parameters for the proposed prototype, shown in Table 18 (below), were decided upon by considering the socio-economic constraints of an illustrative middle-income household described in Table 15 (above), together with the deficiencies of the existing commercial technologies considered in this study.

Table 18: Prototype design parameters

Purchase price	< R16 870.89 (50% of max. monthly household income)
Greywater sources	Showers, baths, wash hand basins and laundry facilities
Treatment device footprint	< 1 m ²
Treatment device mobility	Fully portable
Treatment device construction	Modular, easy to maintain
Treatment device operation	Manual, with the possibility for automation
Required treatment capacity	222 to 444 litres per day
Major service intervals	365 days
Minor service intervals	2 months
No. of electro-mechanical components	≤ 1
Tertiary filtration?	Yes
Tertiary disinfection?	Manual chemical disinfection preferred.
Influent water quality	As per Table 5 (NSF/ANSI 350) (i.e. synthetic greywater)
Effluent water quality	As per Table 16 (i.e. fit for toilet flushing¹¹, clothes washing and surface cleaning only)

3.3.2 Prototype concept

A number of concepts were generated. Through a process of critical evaluation, the concept selected is provided in Figure 20 (below).

The proposed prototype concept consists of four vertically arranged cylindrical chambers. Raw greywater enters the top of the treatment device and treated greywater is extracted from the bottom of the device. A nylon sock is sandwiched between a backing nut and the ceiling of the first cylindrical section of the treatment device, to provide pre-screening of the raw greywater for removal of lint and particulates (inorganic and organic, settleable and non-settleable).

¹¹ Untreated greywater is suitable for toilet flushing, provided it is used within 24 hours from generation

The pre-filtered greywater then passes through a second cylindrical section below the first section, where biological treatment is augmented using (polypropylene based) attached growth media. The media is packed and designed in such a way as to prevent the inhibition of greywater flow even after excessive growth of the biological “slime” layer on its surface. The sludge is activated through the supply of oxygen rising from the third cylindrical section below the second section. As the biologically treated greywater passes through the second cylindrical section and into the third below, particulates and dissolved solids will flow over a ribbed conical section at the base of the second cylindrical section which penetrates into the top of the third section below. The ribbed inserts are concentric. Perforations are made along the wall of the conical section, beneath each concentric rib. It is through these perforations that oxygen is allowed to flow between the third section and the second section. The presence of the concentric ribs ensures that particulates do not flow through the perforations, which would otherwise result in the short-circuiting of flow. The supply of oxygen through the perforations also ensures a slightly positive pressure on the outside of the conical section, preventing dissolved solids from passing through.

The biologically treated wastewater flows through the conical section to a small cylindrical chamber at the base of the third cylindrical section. This small cylindrical chamber performs the function of a settling tank, whereby settleable particulates fall to the bottom. An air-driven Venturi pump and sludge conveyor pipe will allow for the recirculation of the settled sludge from the third cylindrical section into the first cylindrical section receiving pre-filtered greywater.

Non-settleable (and dissolved) solids will be conveyed with the biologically treated greywater towards the perimeter of the third cylindrical section. Non-settleable solids will continue to float upwards, assisted through dissolved air flotation (provided by means of a perforated, raised, oxygen delivery pipe on the floor of third chamber), eventually passing through the perforations in the conical section and rising into the attached growth media (similar to an up-flow biological reactor).

Biologically treated and clarified greywater will be received by four standard 9” gravity driven microfiltration (activated carbon) cartridges to provide tertiary filtration. The provision of air through the delivery pipe at the base of the third cylindrical section, alongside the filtration elements, will allow for air scouring over the filtration elements, reducing fouling and prolonging their service life. The use of filtration elements will assist in the removal of suspended solids not removed through settling at the centre of the third cylindrical section. Furthermore, it allows for a larger solids concentration within the biological reactor (as clarification is no longer only achieved through settling).



The filtered water will then pass into a fourth and final cylindrical section which forms the base of the treatment device. It is envisaged that the end-user will opt to disinfect the treated greywater manually after extraction from the treatment device, through chemical disinfection. However, a UV-C disinfection lamp can very easily be provided in the fourth chamber, if desired by the end-user.

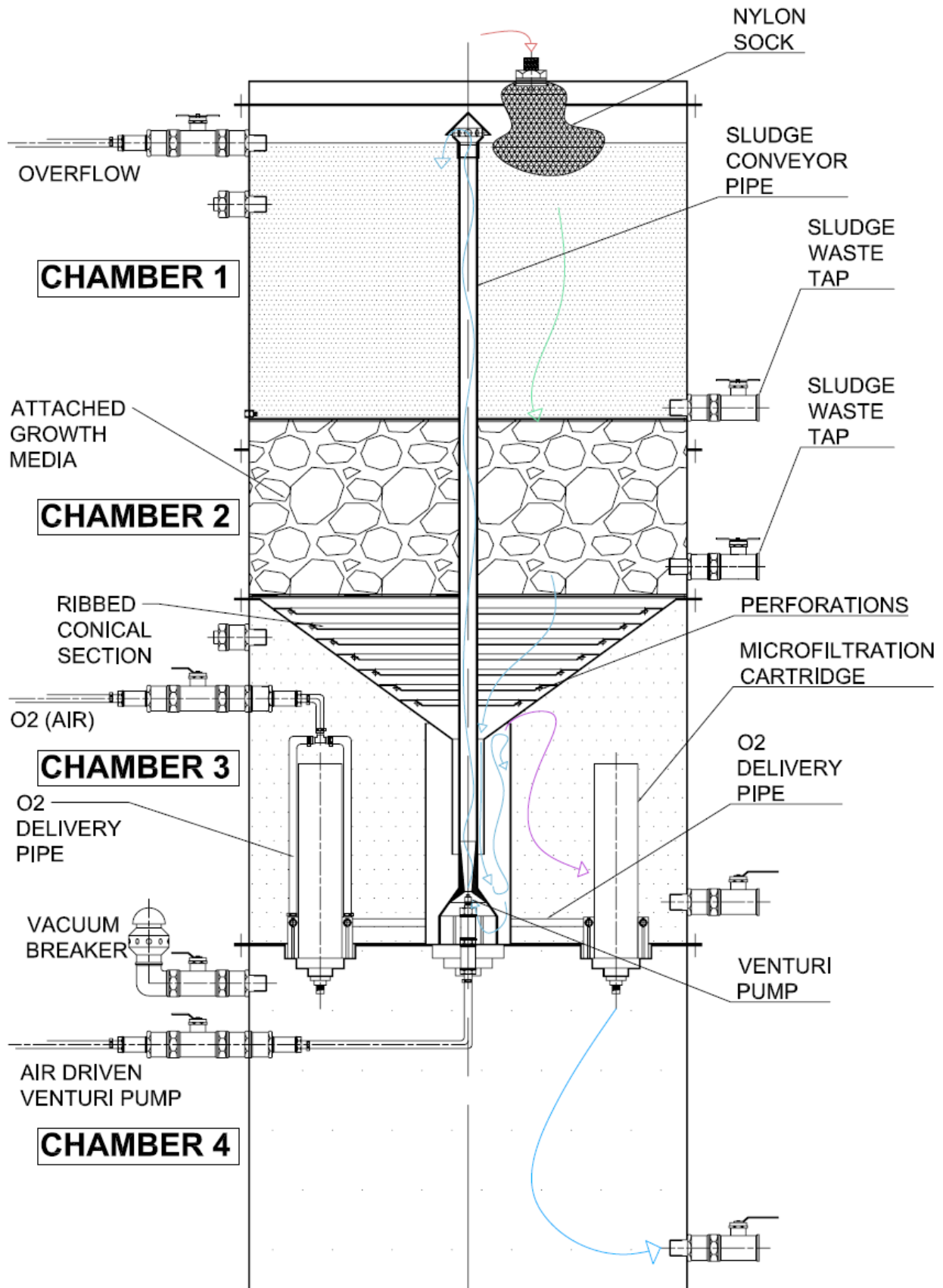


Figure 20: Prototype concept design. Refer to Annexure A for further detail.

3.3.3 Detailed design

The design process consisted of three stages, the first entailing the representation of the prototype as a process flow diagram. In the second design stage, a mathematical model is selected to characterise the treatment process. In the third design stage, the volume of greywater that can be treated by the proposed prototype design, already sized by end-user constraints, will be determined.

3.3.3.1 Process description

The prototype design above was first represented using a process flow diagram, shown in Figure 21 (below), from which the appropriate mathematical model was selected.

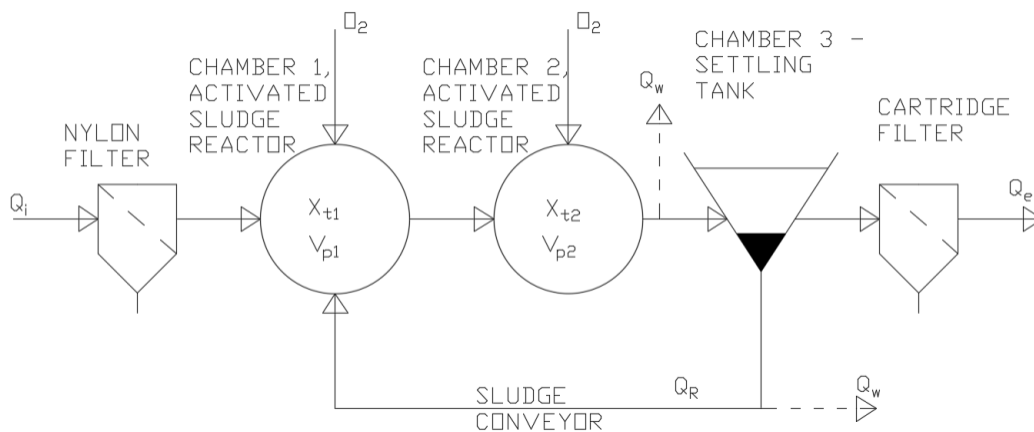


Figure 21: Prototype design concept represented as a process flow diagram

Biological treatment is expected to take place (using activated sludge) in chamber 1 and chamber 2 (i.e. atop the surface and within the voids of the attached growth media). With the use of attached media (i.e. biofilms), active biomass concentrations (and thus COD removal) are expected to be much higher when compared to conventional activated sludge systems (where the biomass remains in suspension in the bulk liquid) (Henze et al., 2008). However, given the scope of this minor dissertation and the complexity involved in modelling the growth and detachment of such biofilms (containing several groups of organisms in its various layers) using analytical and multidimensional numerical models, its effect on the overall performance of the prototype was neglected, resulting in a conservative design. The above process was further simplified to the one illustrated in Figure 22 (below), treating chamber 1 and 2 as a single biological reactor with Total Suspended Solids (TSS) concentration, X_t {mg/l}, and reactor volume, V_p {litres}.

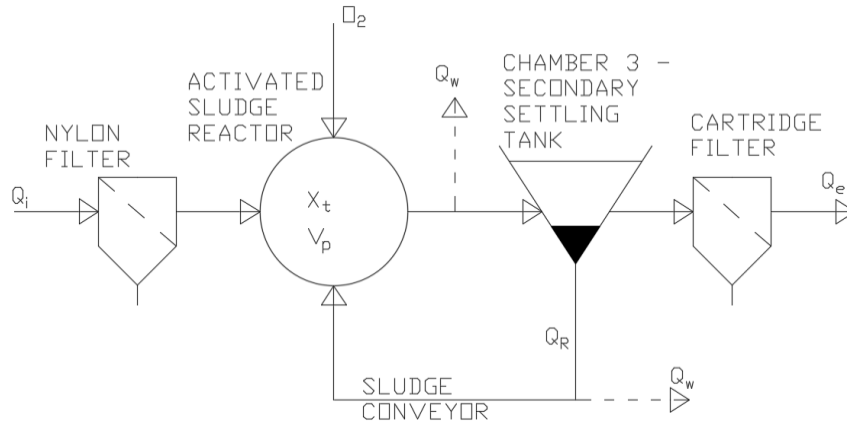


Figure 22: Prototype design concept represented as a simplified process flow diagram

The process description described in Figure 22 is comparable to that of the Activated Sludge (AS) treatment process (Figure 23). It is for this reason that the Activated Sludge model was used to describe the treatment process of the prototype design.

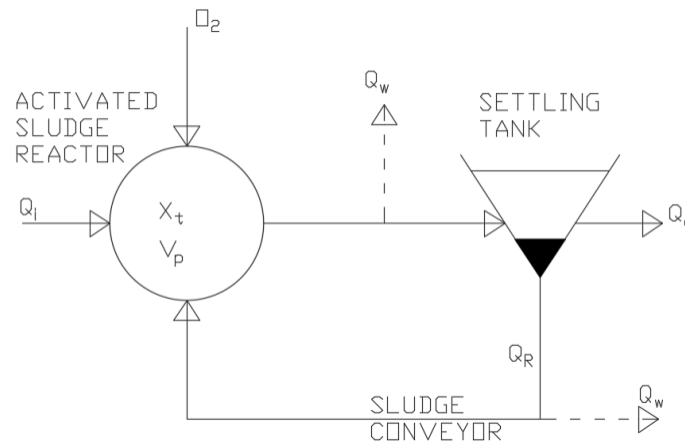


Figure 23: Conventional Activated Sludge (AS) treatment process

3.3.3.2 Mathematical model generation

In the development of the mathematical model, using the (simplified) process description shown in Figure 22, a control volume (shown in Figure 24, below) was defined such that the appropriate laws of conservation (mass and flow) could be applied; the result of which is the Activated Sludge model (for organic matter removal only) (Henze et al., 2008)¹².

¹² Derivations pertaining to AS theory are not included in this thesis. The reader is referred to (Henze et al., 2008)

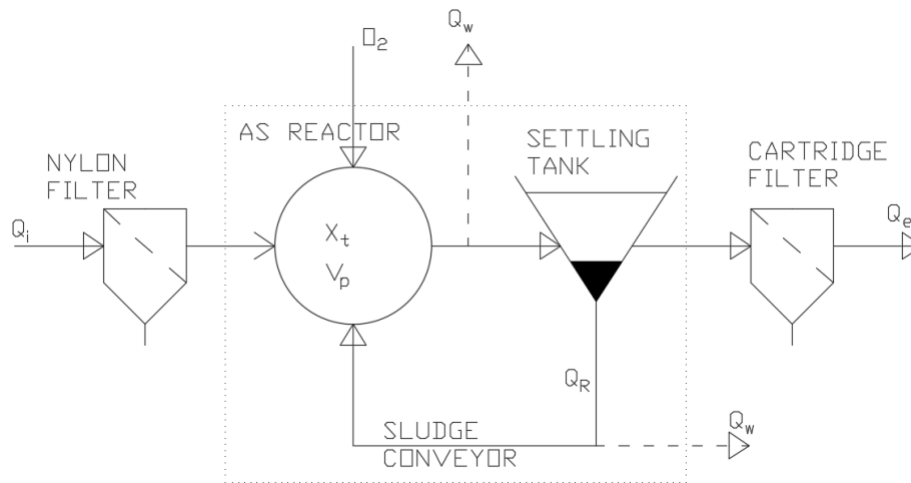


Figure 24: Control volume established around the AS system which represents the prototype design.

Model assumptions

In the application of AS theory for the detailed design of the prototype, the following assumptions were made.

- (i) All particulates passing through the biological reactor (i.e. chambers 1 and 2 of Figure 20) become settleable due to bioflocculation, settling in the centre of the settling tank (i.e. chamber 3 of Figure 20).
- (ii) All particulates settle at the centre of the settling tank (i.e. chamber 3), some of which are returned to the biological reactor by the action of the Venturi pump through the sludge conveyor.
- (iii) All biodegradable organics, soluble and particulate, are utilised in the biological reactor.
- (iv) Degradation of organic matter is by aerobic respiration only.
- (v) The mass of active autotrophic organisms in the bioreactor is negligible in comparison to the mass of heterotrophic organisms in the bioreactor.
- (vi) Spaces in between the individual elements which constitute the attached growth media are sufficient to prevent the inhibition of particulate flow through the biological reactor.
- (vii) The provision of air directly into chamber 3, together with a positive pressure barrier and perforations in the ribbed conical section, will ensure that no mixing takes place between the centre and outer perimeter of chamber 3.
- (viii) Dissolved oxygen is distributed evenly throughout the reactor, resulting in a fully aerobic AS treatment process.
- (ix) End users of the treatment device will only make use of detergents and cleaning products conducive to the biological treatment of wastewater (eg. PROBAC[®] Laundry Detergent)

Following the assumptions above, the reactor volume and “settling tank” provided by the prototype design was described as shown in Figure 25 and Figure 26, respectively. Detailed drawings of the prototype design are provided in Annexure A.

Typically, in the design of an AS reactor, the influent flow and influent COD concentration are known. In such cases, the objective of the AS design procedure is to determine, among other things, the reactor volume required to treat the influent COD flux.

In this design approach the available reactor volume (and influent COD concentration) was fixed, to suit the space constraints of the end user and to allow for the use of readily available materials for its construction to negate the need for custom manufacturing of components. Standard 210L metallic drums (approximately 575mm outer diameter), typically used for the transport of oil, were seen as appropriate for the construction of the 4 chambers (and lid) which constitute the prototype design. The available reactor volume was calculated to be 169L, which consists of the volume provided by chamber 1 and 2 and of the volume provided by the conical section below chamber 2.

The cylindrical section in the lower half of chamber 3 was modelled as a secondary settling tank (SST), illustrated in Figure 26. As with conventional SSTs, it is assumed that there is complete separation between the overflow (Q_i) and underflow (Q_R) to provide a clear effluent (Q_E) when under loaded. In the SST of the prototype design, suspended solids settle to the bottom of the cylindrical section and are recirculated to the biological reactor (i.e. chamber 1 and 2 above) via the underflow return by means of a Venturi pump and sludge conveyor pipe.

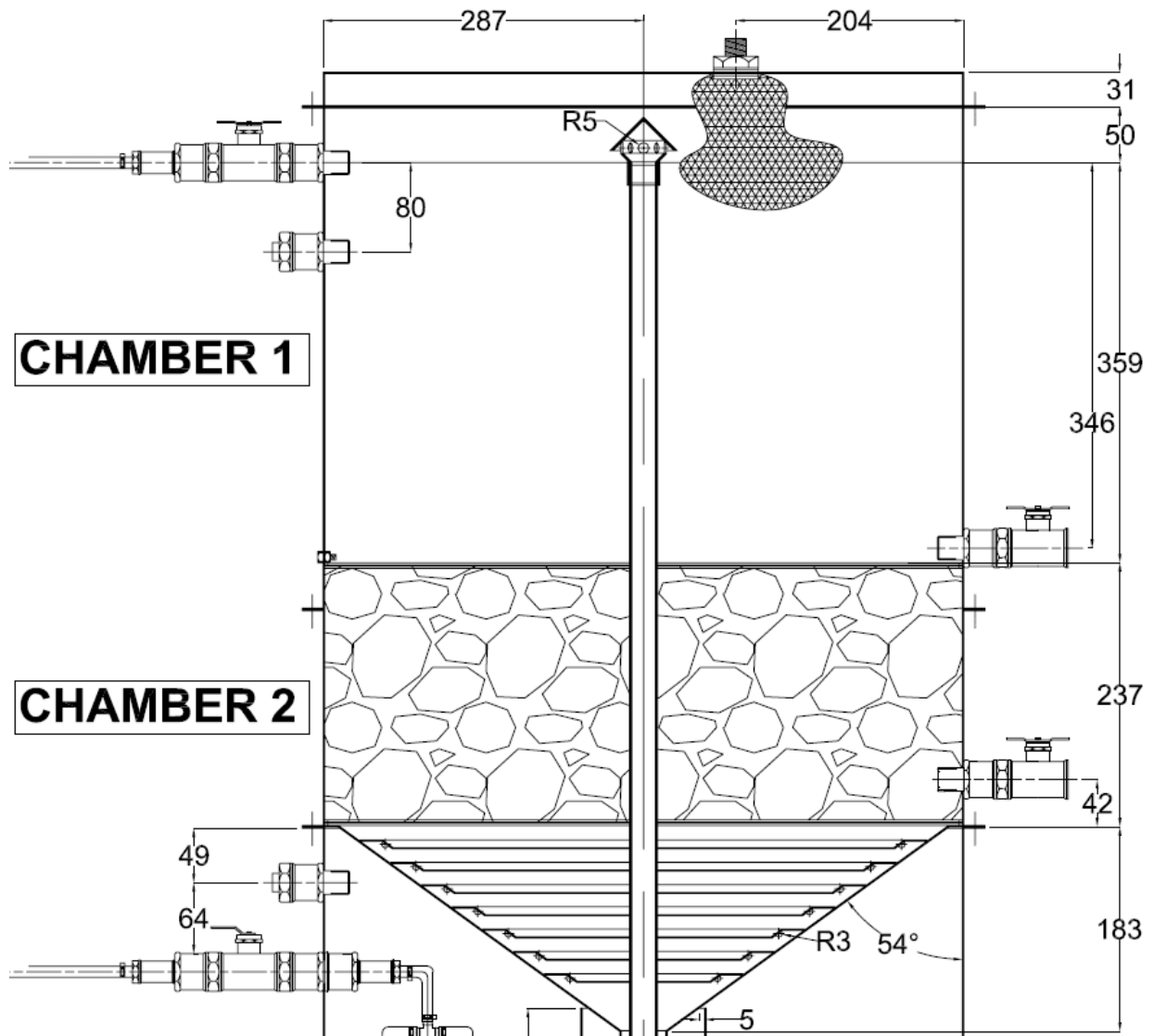


Figure 25: Prototype reactor volume (internal diameter 572mm), providing a reactor volume of approximately 169 litres.

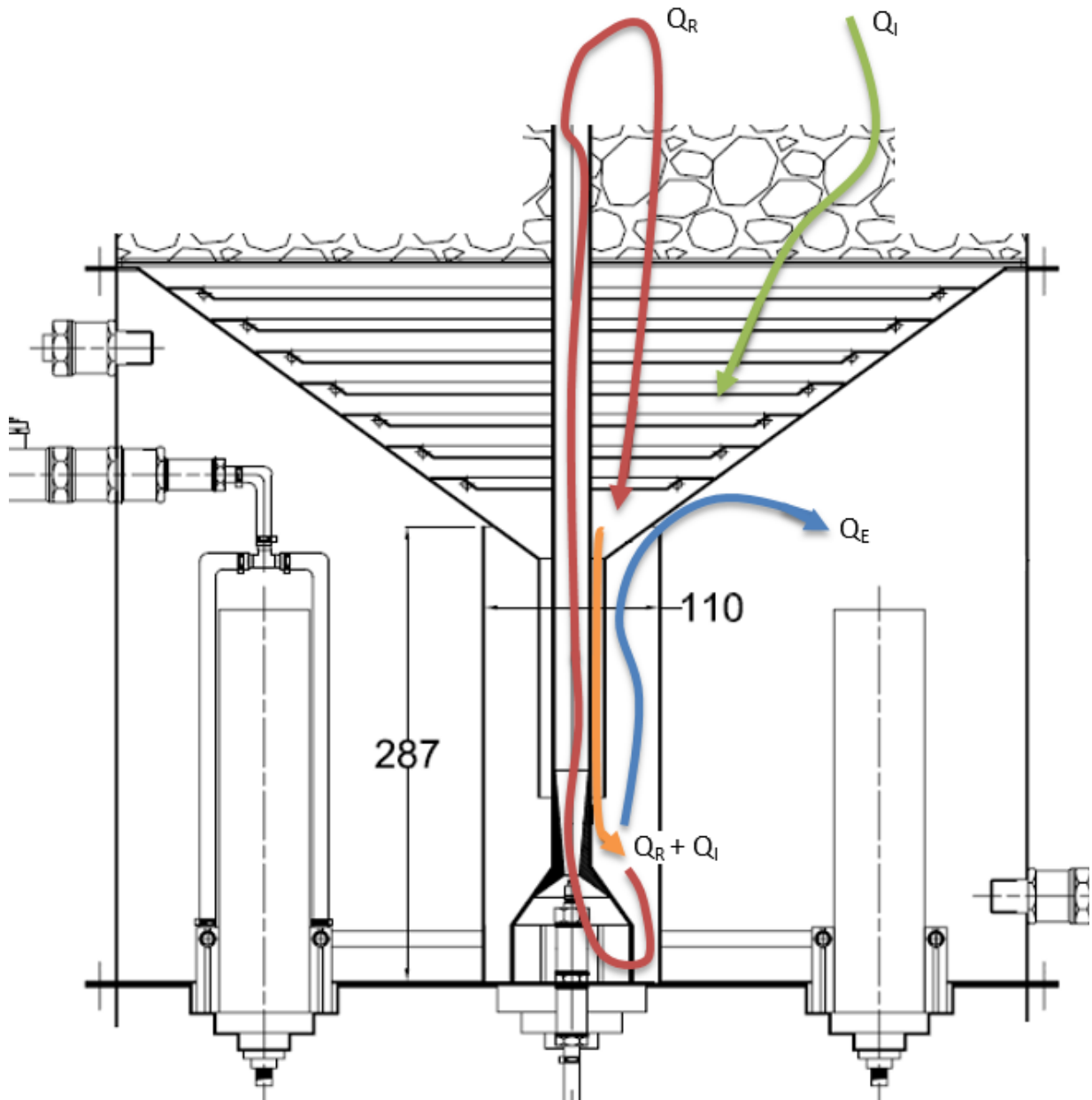


Figure 26: Cylindrical section in the lower half of chamber 3 modelled as a secondary settling tank.

3.3.3.3 Detailed design calculations

Wastewater and sludge characterization

Stoichiometric and kinetic constants, followed by the complete characterization of the grey wastewater and the sludge produced through aerobic biological treatment are summarised in Table 19, 20 and 21 (below). Unless stated otherwise, characteristic values are based upon those typically observed in municipal wastewater AS treatment systems receiving raw wastewater, producing poor settling sludge and only concerned with organic matter removal (Henze et al., 2008).

Table 19: Kinetic and stoichiometric activated sludge constants required for detailed design of prototype concept

Kinetic and Stoichiometric Constants	Symbol	Unit	Value
OHO Yield	Y_{Hv}	mgVSS/mgCOD	0.45
OHO kinetic growth constant	K_v	l/mgVSS.d	0.07
Specific rate of endogenous mass loss of OHOs	b_{H20}	d ⁻¹	0.24
Unbiodegradable fraction of OHO	f_{EH}	mgVSS/mgVSS	0.2
Inorganic Suspended Solids (ISS) content of OHO	f_{iOHO}	mgISS/mgVSS	0.15
Nitrogen content of OHOs	f_n	mgN/mgVSS	0.10
Phosphorus content of OHOs	f_p	mgP/mgVSS	0.025
COD/VSS Ratio of activated sludge	f_{cv}	mgCOD/mgVSS	1.5
Maximum specific growth rate ANOs	μ_{Am20}	d ⁻¹	0.45
Half saturation coefficient ANOs	K_{n20}	mgN/l	1.0
Specific rate of endogenous mass loss of ANOs	b_{n20}	d ⁻¹	0.04

Table 20: Activated sludge characteristics required for the detailed design of the prototype concept

Sludge characteristics	Symbol	Unit	Value
Unaerated sludge mass fraction	f_{xt}	-	0.00
Sludge age ¹³	R_s	days	10
Diluted sludge volume index ¹³	$DSVI$	ml/g	120
Reactor TSS concentration	X_t	kgTSS/m ³	TBD

¹³ Sludge age is controlled hydraulically, opening the diaphragm valve labelled "sludge waste tap" (shown in Figure 20) and wasting directly from the attached growth chamber. The DSVI selected is that of poor settling sludge, to provide a conservative prototype design

Table 21: Influent wastewater properties required for detailed design of prototype concept

Influent wastewater characteristics	Symbol	Unit	Value
Influent flow rate	Q_i	L/d	TBD
Peak flow factor	f_q	-	2.5
Wastewater temperature (min/max) ¹⁴	T	°C	13/28
Fraction of influent unbiodegradable particulate COD ¹⁵	$f_{S'_{up}}$	mgCOD/mgCOD	0.015
Fraction of influent unbiodegradable soluble COD ¹⁵	$f_{S'_{us}}$	mgCOD/mgCOD	0.050
Total influent TKN (synthetic greywater NSF/ANSI 350)	N_{ti}	mgN/l	3.0
Total influent TP (synthetic greywater NSF/ANSI 350)	P_{ti}	mgP/l	1.0
Total influent COD (synthetic greywater NSF/ANSI 350)	S_{ti}	mgCOD/l	400
Fraction of ISS per mgCOD in influent	X_{IOi}/S_{ti}	mgISS/mgCOD	0.1

Determination of prototype treatment capacity

The first step executed in the calculation procedure was the correction of the kinetic constants for the minimum design temperature. As sludge production is greater at lower temperatures, biological reactors must be sized for the minimum operational wastewater temperature. The calculation procedure would then be repeated for the maximum operational wastewater temperature, but with the reactor volume (V_p) fixed (at 169 litres), as nitrification increases with an increase in wastewater temperature.

The specific rate of endogenous mass loss for OHOs at a temperature of 13°C was corrected as follows.

$$\begin{aligned}
 b_{HT} &= b_{H20}(1.029)^{T-20} & (1) \\
 &= 0.24(1.029)^{13-20} \\
 &= 0.1965 \{d^{-1}\}
 \end{aligned}$$

The COD concentration expected in the reactor was then calculated as follows.

$$S_b = \frac{1 + b_{HT}R_s}{Y_{Hv}R_sK_v} \quad (2)$$

¹⁴ A large temperature range was specified (informed by typical ambient temperatures experienced in the City of Cape Town), whilst considering the fact that household greywater may be warm immediately after it is produced. If the end-user chooses to house the treatment device in an outside space, then the temperature may reach the minimum value specified during the course of the night.

¹⁵ Hocaoglu, S. M., Insel, G., Cokgor, E. U., Baban, A., & Orhon, D. (2010). *COD fractionation and biodegradation kinetics of segregated domestic wastewater: black and grey water fractions*. Chemical Technology and Biotechnology, 85(9). <https://doi.org/10.1002/jctb.2423>

$$= 9.4119 \left\{ \frac{mgCOD}{l} \right\}$$

From the above calculation it can be seen that the reactor COD concentration is equal to less than 3 percent of the influent COD concentration of 400mgCOD/l. Hence, it is reasonable to assume that the reactor COD concentration is negligible, with the growth of the microorganisms in the reactor only dependent upon the influent biodegradable COD load.

The mass of total suspended solids (TSS) in an AS reactor, for a sludge age of R_s days, is calculated using the formula

$$MX_t = A \cdot Q_i S_{ti} \quad \{kgTSS\} \quad (3)$$

Where

$$\begin{aligned} A &= (1 - f_{s'up} - f_{s'us}) \left(\frac{Y_{Hv} R_s}{1 + b_{HT} R_s} \right) (1 + f_{EH} b_{HT} R_s + f_{iOHO}) \dots \\ &\dots + \left(\frac{f_{s'up}}{f_{cv}} + \frac{X_{IOi}}{S_{ti}} \right) R_s \\ &= 3.2897 \left\{ \frac{kgTSS \cdot d}{kgCOD} \right\} \end{aligned} \quad (4)$$

Flux Theory (Ekama & Marais, 1986) together with Activated Sludge (AS) Theory, was applied to determine the maximum allowable reactor TSS concentration and influent flow, such that the sludge handling capacity of chamber 3 was not exceeded. In the application of the Flux Theory, a flux reduction of 20% was applied.

Using the SSVI and DSVI relationship derived by (Ekama & Marais, 1986), from 15 Western Cape Plants,

$$SSVI = 0.67 DSVI \quad (5)$$

$$\therefore SSVI = 80.4 \left\{ \frac{ml}{g} \right\}$$

Deriving the flux theory constants using the relationships as described by (Ekama & Marais, 1986; Pitman, 1984, 1980),

$$\frac{V_o}{n} = 67.9 \exp(-0.016 \cdot SSVI) \quad (6)$$

$$= 18.7583 \left\{ \frac{kg}{m^2 \cdot h} \right\}$$

And

$$n = 0.88 - 0.393 \text{Log} \left(\frac{V_o}{n} \right) \quad (7)$$

$$= 0.3796 \left\{ \frac{l}{g} \right\}$$

Thus

$$V_o = n \left(\frac{V_o}{n} \right) \quad (8)$$

$$= 7.1213 \left\{ \frac{m}{h} \right\}$$

The projected surface area (diameter 110mm) provided by the internal cylindrical section within chamber 3, acting as the SST, was calculated as,

$$A_{SST} = \frac{\pi D^2}{4} \quad (9)$$

$$= 9.5033 \times 10^{-3} \{m^2\}$$

Next, input variable B , based upon the requirement to satisfy Sludge Handling Criteria II as described by Flux Theory (Ekama & Marais, 1986), was calculated (with a factor of safety of 20%) as

$$B = \frac{\left(1 - \frac{20}{100}\right) A_{SST} V_o 24}{1000 f_q} \quad (10)$$

$$= 5.1975 \times 10^{-4} \left\{ \frac{ML}{d} \right\}$$

Such that

$$C = A \cdot B \cdot \frac{S_{ti}}{V_p} \quad (11)$$

$$= 4.0511 \left\{ \frac{kgTSS}{m^3} \right\}$$

And

$$X_t = C \cdot \exp(-nX_t) \left\{ \frac{kgTSS}{m^3} \right\} \quad (12)$$

To calculate the (maximum) biological reactor concentration, X_t , an iterative calculation procedure is applied, yielding a reactor TSS equal to 1.9398 {kgTSS/m³}. Finally, with the calculated reactor TSS concentration, the allowable influent flow to the prototype (i.e. ADWF) was calculated as

$$Q_i = B \cdot \exp(-nX_t) \times 10^6 \quad (13)$$

$$= 248.8737 \left\{ \frac{l}{d} \right\}$$

Less the waste flow, Q_w , calculated as

$$Q_w = \frac{V_p}{R_s} \quad (14)$$

$$= 16.8829 \left\{ \frac{l}{d} \right\}$$

Thus, the treated greywater produced equates to 232 {litres/day}.

The above calculation result indicates that the prototype design concept will be capable of meeting the end-user requirements, with regards to treatment capacity and footprint, *when considering the wastewater and sludge properties as defined in Tables 19 to 21.*

Energy requirements

Given the increased levels of endogenous respiration at warmer temperatures, the daily carbonaceous oxygen demand required to support the above biological treatment process was calculated using an endogenous respiration rate corrected (using Eq. 1) for a temperature of 28°C.

$$FO_c = Q_i S_{ti} (1 - f_{s'up} - f_{s'us}) \left[(1 - f_{cv} Y_{Hv}) + f_{cv} (1 - f_{EH}) \cdot b_{HT} \cdot \frac{Y_{Hv} R_s}{1 + b_{HT} R_s} \right] \quad (15)$$

$$= 68.3175 \left\{ \frac{gO}{d} \right\}$$

Considering the density of Oxygen (ρ_o) at NTP conditions (1.331kg/m³), together with the fact that the fraction of Oxygen present in the atmosphere (f_{o2}) equates to approximately 21% (by volume), the daily air demand (Q_{AC}) can be calculated as

$$Q_{AC} = FO_c \cdot \left(\frac{1}{\rho_o} \right) \cdot \left(\frac{1}{f_{o2}} \right) \cdot \left(\frac{1}{24} \right) \cdot \left(\frac{1}{60} \right) \quad (16)$$

$$= 0.1697 \left\{ \frac{\text{litres Air}}{\text{minute}} \right\}$$

The above Oxygen demand can easily be met by the smallest of pumps available on the market, such as the 8.5W HIBLOW CD 8S linear air pump (Annexure E), even at poor oxygen transfer efficiencies. This same pump may then also be used to supply air (intermittently) to the Venturi pump for sludge conveyance.

Nutrient requirements

Next, it is necessary to determine whether or not a sufficient amount of nutrients exist in the raw influent wastewater to allow for the proliferation of the OHO microorganisms (at the minimum wastewater temperature of 13°C). The Nitrogen and Phosphorus requirements for OHO growth, per litre influent, were calculated as follows.

The mass of organic volatile suspended solids (VSS) in the reactor was calculated as

$$MX_v = FS_{ti} \left[(1 - f_{S'up} - f_{S'us}) \cdot \frac{Y_{Hv}R_s}{1 + b_{HT}R_s} \cdot (1 + f_{EH}b_{HT}R_s) + \frac{f_{S'up}R_s}{f_{cv}} \right] \quad (17)$$

$$= 0.2069 \{kgVSS\}$$

The nitrogen and phosphorus requirements were then calculated as

$$N_s = \frac{f_n MX_v}{R_s Q_i} \quad (18)$$

$$= 8.3125 \left\{ \frac{mgN}{litre\ influent} \right\}$$

And

$$P_s = \frac{f_p MX_v}{R_s Q_i} \quad (19)$$

$$= 2.0781 \left\{ \frac{mgP}{litre\ influent} \right\}$$

From the above it can be seen that, due to the low influent TKN and TP concentration, the wastewater may be deficient in nutrients and inhibit biological treatment. Hence, the addition of nutrients into the wastewater stream may be needed. However, this is heavily dependent upon the daily routine of the end user and can only truly be established with site-specific wastewater characterisation.

One may also conclude that, given the very low nitrogen (i.e. TKN) content of the influent wastewater (relative to the influent COD, with a TKN to COD ratio less than 2%), it is unlikely that significant nitrification will occur as little FSA is available for ammonia nitrifying organisms. Thus, the pH of the effluent should remain within an acceptable range (6.0 – 9.0). It is for the same reason that the above calculations were not repeated for warmer greywater temperatures which typically result in increased nitrification, as OHOs will dominate the biological treatment process.

Sludge stability

In the activated sludge treatment process, it is necessary to obtain a measure of the stability of the sludge produced. This is determined by calculating the fraction of active biomass remaining in the sludge (at the minimum wastewater temperature).

$$f_{av} = \frac{MX_{BH}}{MX_v} \quad (20)$$

The mass of active OHO biomass which exists within the reactor (between major service intervals) is calculated as

$$\begin{aligned} MX_{BH} &= Q_i S_{ti} (1 - f_{s'up} - f_{s'us}) \cdot \frac{Y_{Hv} R_s}{1 + b_{HT} R_s} \\ &= 0.1413 \{kgVSS\} \end{aligned} \quad (21)$$

Thus, the active mass fraction was calculated to be 0.6829 {mgVSS/mgVSS}. The remaining active fraction of biomass is shown to be high, indicating an unstable sludge mass with a significant proportion of biodegradable matter (i.e. energy content) remaining. This is to be expected for short sludge age systems of 5 to 10 days. However, this is inconsequential to the user, as the waste activated sludge is discharged to a sanitary drain.

COD balance

It is necessary to perform a COD balance to ensure that the laws of conservation are satisfied in the AS treatment process. This is done by considering the flux of COD into the AS treatment system and the flux of COD out of the reactor (at either the minimum or maximum wastewater temperature).

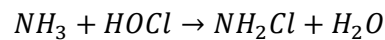
$$\begin{aligned} FS_{ti} &= f_{s'us} Q_i S_{ti} + FO_c + \frac{f_{cv} MX_v}{R_s} \\ 99.5495 &= 4.9775 + 63.9336 + 30.6384 \left\{ \frac{gCOD}{d} \right\} \end{aligned} \quad (22)$$

The COD balance at the minimum wastewater temperature is shown above. When performing the preceding calculations at both minimum and maximum wastewater temperatures, a COD balance of 100.0000% is achieved. The small tolerance to which a COD balance was achieved is expected, as the design calculations are based upon theoretical values and not experimental data.

Disinfection

Disinfection is either performed through broad spectrum ultraviolet (i.e. UV-C) irradiation or (manual) chemical disinfection upon extraction of the treated wastewater.

Chemical disinfection is most often performed through the use of Chlorine (or Sodium Hypochlorite, the primary constituent of household bleaching agents). As Ammonia is typically present in wastewater, a large portion of the Chlorine added is converted to Chloramines (NH_2Cl).



The above must be taken into account when determining the total Chlorine demand for disinfection. However, as was already shown for the sludge nutrient requirements, little Ammonia (i.e. FSA) will remain in biologically treated household greywater. Hence, for chemical disinfection, achieving a Chlorine concentration of 5mg/l (as prescribed by the World Health Organization for turbid waters) should suffice (World Health Organization., 2006). When using a household liquid sodium hypochlorite chemical disinfectant (with 3.5% or 35g/l of active chlorine) to disinfect the 232l of treated greywater produced per day, approximately 33ml of sodium hypochlorite is needed per day. Equation 23 (below) shows how the volume of disinfectant was calculated, prior to partially being consumed by in-situ contaminants, where C_1 is the initial active chlorine concentration of the disinfectant, V_1 the volume of disinfectant to be added, C_2 the active chlorine concentration of the treated greywater, and V_2 the volume of the treated greywater produced in a day.

$$C_1 \cdot V_1 = C_2 \cdot V_2 \quad (23)$$

$$\begin{aligned} \therefore V_1 &= \frac{5mg \text{ active Cl}}{1 \text{ litre}} \times 232 \text{ litres} \times \frac{1 \text{ litre}}{35 \times 10^3 mg \text{ active Cl}} \\ &= 33 \text{ ml sodium hypochlorite (at 3.5\%)} \end{aligned}$$

Disinfection requirements through the use of UV-C are typically determined through the consideration of three factors, with the prototype design specifications provided alongside:

- (i) Water quality – Treated wastewater for reuse (Turbidity >2 NTU and <5 NTU)
- (ii) Peak flow rate – 232L per day, or 9.7L per hour over 24 hours
- (iii) Pathogen removal requirements – Removal of *Escherichia coli* (*E. coli*) to < 1CFU/100mL

An important feature of any UV-C disinfection unit is the UV dose which the device can provide. The necessary dose required is specific to pathogen removal requirements and is heavily influenced by water quality, peak flow rate (i.e. hydraulic retention time), fouling characteristics and geometrical

features. It is for this reason that the dose rating of any UV lamp is specific to its construction and is proprietary to manufacturers. Instead, a supplier will most often provide a UV disinfection unit considering the above three parameters and will not explicitly specify the dose which is supplied by the UV disinfection unit. For the reader's own interest, the formula used for the calculation of dose is typically defined as (SUEZ, 2018),

$$Dose = I_{avg} \cdot t' \cdot \frac{\theta}{t'} \cdot f_h \cdot f_{lmp} \cdot f_t \quad \left\{ \frac{\mu W \cdot s}{cm^2} \right\} \quad (24)$$

Standards as defined by the United States of America (National Water Research Institute, 2012; United States Environmental Protection Agency (EPA), 2012) specify that, for unrestricted urban reuse of treated wastewater when using non-membrane filtration upstream of UV disinfection (as may be the case with the prototype design presented in this dissertation), a minimum dose of 100mJ/cm² (or 100 mW.s/cm²) is required. Furthermore, filtered effluence transmittance must be equivalent to 55% or greater for a wavelength of 254nm.

Hence, when selecting an appropriate UV disinfection unit, it must be confirmed with the manufacturer whether or not the unit provides the appropriate dose (i.e. 100mJ/cm²). For the purposes of the prototype design, a UV-C lamp (to be housed within chamber 4 of Figure 20) rated at 4W was selected, if UV disinfection were to be selected by the end user.

Concluding remarks

Designing the prototype with a reactor volume as calculated above, with the assumed wastewater properties, will result in the production of an effluent with a COD that falls within the limits established for the prototype design (i.e. <30mgCOD/l). Based upon the assumed wastewater and sludge characteristics, the biological reactor concentration and permitted influent flow was calculated to ensure that the sludge handling capacity of the prototype's settling chamber was not exceeded. Hence, it can be deduced that, when operating within these limits, the prototype should be capable of producing treated effluent with a low suspended solids concentration (i.e. <30mgSS/l as is achieved with conventional secondary settling tanks used in the AS treatment process). Furthermore, it is expected that the use of filtration elements in chamber 3, together with the design features of the prototype design, will result in the compliance of the effluent quality with regards to TSS and turbidity as specified in Table 16.

When treating wastewater through the Activated Sludge treatment process, it is safe to assume that at least 40% of all pathogens are removed as a result of bioflocculation and sedimentation in the centre of chamber 3 (Henze et al., 2008). It is further expected that the use of chemical disinfection

or broad spectrum ultraviolet radiation will destroy any coliforms, including E. Coli, which may still be present following biological treatment and tertiary filtration.

3.3.4 Detailed design drawings

The invention will now be described in more detail, by way of example only, with reference to the accompanying drawings (provided in Annexure A) in which:

- **Figure A-1.1** shows a front view of a compact greywater recycler, according to the present invention;
- **Figure A-1.2** shows a sectioned front view of a compact greywater recycler, according to the present invention;
- **Figure A-1.3** shows a sectioned top view of a compact greywater recycler, according to the present invention;
- **Figure A-1.4** shows a bill of quantities and materials, according to the present invention;
- **Figure A-2** shows a magnified view of the attached growth chamber, according to the present invention;
- **Figure A-3** shows a magnified view of the baffle chamber and the conical section, according to the present invention;
- **Figure A-4** shows a magnified view of the sludge conveyor, according to the present invention;
- **Figure A-5** shows a magnified view of filtration elements housed atop the baffle insert within the baffle chamber, according to the present invention;
- **Figure A-6** shows the expected hydraulic flow pattern, according to the present invention;
- **Figure A-7** shows the internal dimensions of the compact greywater recycler, according to the present invention;

The compact greywater recycler composes of 4 chambers, constructed through the assembly of custom cylindrical components. The height of each chamber is sized to provide a reactor volume, V_p , of approximately 170 litres. Once assembled, the recycler stands (vertically) at approximately 1.6m tall, with a diameter of 572mm at its base. Each custom cylindrical component is joined together at their base, through the use of 8 (eight) bolted connections (items 9 and 10 of Figure A-1.1), spread evenly along the circumference. Each cylindrical section may be manufactured using standard (off-the-shelf) 210L steel drums, which may be coated with an elastomeric polyurethane coating to prevent corrosion. The use of elastomeric polyurethane coated steel over fiberglass or polyurethane will decrease the cost of manufacturing significantly.

Water tightness is ensured through the use of rubber gaskets at each joint. All fittings include the appropriate rubber seals to ensure that all tank penetrations and off-the-shelf assemblies are watertight. All constituents of the compact greywater recycler are assigned item numbers in Figures A-1.1 to A-1.3, along with the corresponding quantities and material of construction for each item as described in the Bill of Materials (Figure A-1.4).

The first chamber, labeled as item 4 of Figure A-1.1, makes use of a nylon screen (item 31 of Figure A-1.2), which is sandwiched between the backing nut (item 11 of Figure A-1.1) and the chamber cap (item 5 of Figure A-1.1). This allows for the easy attachment of the nylon screen, to provide pre-screening of the greywater. The first chamber may receive the greywater either manually or through a pumped supply, made possible through the construction of the chamber cap, which can facilitate the addition of a quick release hose connection atop the chamber cap. Standard, off-the-shelf components (such as quick release couplings) can be used to connect to the compact greywater recycler.

The greywater then passes through the second chamber, defined as the attached growth chamber (item 3 of Figure A-1.1), which contains media (item 30 of Figure A-1.2) designed to provide a large surface area on which the biomass (i.e. biofilm) may grow. The media is sandwiched between two mesh screens (item 29 of Figure A-1.2) to prevent them from floating to the surface. Sludge age is controlled hydraulically, opening the diaphragm valve labelled “sludge waste tap” (shown in Figure 20) and wasting directly from the attached growth chamber. The sludge age is fixed by the position of this diaphragm valve; with the position of the valve fixed, together with a constant head, the flow of mixed liquor wasted (Q_w) is kept at the desired setpoint of 16.9 litres per day. A constant head may be provided by making use of an external “raw” water tank and pump which continuously pumps greywater into the top of the treatment device. The overflow pipe for Chamber 1 of the treatment device would then be connected to the same raw water tank. This would be the most ideal solution to controlling sludge age if the sludge waste tap was permanently connected to a sanitary drain. As an alternative, if the user does not make use of a permanent sanitary drain connection, the user would then ensure that the sludge waste tap is opened once a day to waste the required 16.9 litres of mixed liquor. This approach of course assumes that all the biomass contained within the reactor volume (which includes chamber 1 and 2 and the conical section below chamber 2, as shown in Figure 25) remains in suspension, which will not be the case due to the presence of media within chamber 2. However, as was previously stated (in section 3.3.3.1), the effect of the media’s presence on the overall performance of the prototype lies outside of the scope of this minor dissertation.

The base of the attached growth chamber is shaped as a conical section, with baffle ring inserts (at evenly spaced locations), labeled item 27 of Figure A-1.2. Aeration is provided through a ring of tubing (item 24 of Figure A-1.2 and Figure A-1.3), perforated on its underside, resting on stilts (item 26 of Figure A-1.2 and Figure A-1.3) such that they lie above the floor of the baffle chamber insert (labelled as item 23 of Figures A-1.1 to A-1.3). The baffle chamber insert (item 23) is sandwiched along its circumference, between the flange atop the treated water chamber (item 1 of Figure A-1.1) and the flange at the base of the baffle chamber (item 2 of Figure A-1.1). This construction allows for the infiltration of air provided from the baffle chamber, item 2 of Figure A-1.1, to the attached growth chamber, item 3 of Figure A-1.1, through perforations below each baffle ring insert, labelled item 27 of Figure A-1.2. It also allows for the simultaneous conveyance of suspended solids into the centre of the baffled chamber insert (item 23 of Figures A-1.1 to A-1.3) to promote settling, whilst also preventing the infiltration of suspended solids towards the gravity filtration elements, labeled item 25 of Figure A-1.2. Placing the air delivery rings (item 24 of Figure A-1.3) alongside the circumference of the filtration elements in the baffle chamber will also promote air scouring, prolonging the service life of the filtration elements. At the centre of the baffle chamber is an air operated Venturi pump (item 21 of Figure A-1.2), allowing for transferring of sludge to the first treatment chamber (item 4 of Figure A-1.1) through a sludge conveyor (item 30 of Figure A-1.2). Air, for aeration and sludge conveyance, is delivered by two air supply lines as indicated in Figure A-1.1. The pressurized air supply may be provided by a diaphragm pump, the operating logic of which can be modified to swing between supplying each of the lines to suit process requirements.

Biologically treated water is filtered, under gravity, through four 9" filtration elements, labeled item 25 of Figure A-1.2. The treated water is filtered into a final storage chamber, item 1 of Figure A-1.1, forming the base of the assembly. Chemical disinfection can either take place outside of the chamber, after it is extracted by the user, or, the chamber may accommodate a submersible UV-C lamp, to provide "in-situ" disinfection.

Provision is also made to allow the user, depending on their needs, to extract water from any stage of the treatment process. For instance, if the user requires water for toilet flushing, water can be extracted from the first chamber.

3.3.5 Evaluation of prototype design

The prototype design was evaluated against the same criteria as defined in the evaluation of existing technologies, in an attempt to prove its superiority and novelty.

4. Results

4.1 Summary of existing commercial technologies

Each of the commercial technologies evaluated have been summarised in Table 22 (below), highlighting key features. Each of these features was considered for their evaluation.

Table 22: Summary of existing commercial technological solutions for the CoCT urban consumer to make use of greywater recycling.

Indicator	AQUALOOP 300	Aqua2Use GWTS 500	RECOVER[®]	HYDRALOOP
Extent of direct contact with untreated greywater	- Direct contact every 3-4 months. (Manual cleaning of 0.8mm filter basket carried out.)	- Direct contact every 6 months. (Manual cleaning of the Matala [®] filters in the pre-screening filter.)	- Direct contact every 4 to 6 months. (Manual cleaning of the 100 micron screen filter is recommended.) - Direct contact every 12 months. (Manual cleaning of the treatment vessel is recommended.)	- None (Treatment device is self-cleaning, removing lint and particulates by floatation and skimming when necessary.)
Unpleasant odours	- Rarely emitted	- Rarely emitted	- Rarely emitted	- Rarely emitted
Tertiary filtration	- 0.2micron membrane filter.	- None (Matala [®] Filter Media only incorporated into the biological treatment stage.)	- Inline micro-strainer upstream of pump to cistern.	- None
Tertiary disinfection	- None	- UV-C treatment	- Chlorination (Trichlor tablets, 3" diameter.)	- UV-C treatment

Indicator	AQUALOOP 300	Aqua2Use GWTS 500	RECOVER [®]	HYDRALOOP
Degree of human intervention in its operation	Human intervention only needed during: - annual maintenance activities - troubleshooting	Human intervention only needed during: - annual maintenance activities - troubleshooting	Human intervention only needed during: - annual maintenance activities - troubleshooting	Human intervention only needed during: - troubleshooting
Electro-mechanical components	Electro-mechanical parts include: - suction pump - back-flush pump - blower - float switches - control box	Electro-mechanical parts include: - submersible pump - air water pump x 2 - float switches - control unit - PCB electricals, pressure controls and solenoids etc.	Electro-mechanical parts include: - pressure pump - dye pump - control panel - overflow valve, 3 solenoid valves, pressure transducers and power adapters	Electro-mechanical parts include: - pressure pump - aeration pumps - control panel - control valves, pressure transducers
Purchase Price (excluding taxes) (R13 : \$1 USD) (R16 : 1 Euro)	R65 000.00 Or \$5000.00 USD Or 4 062.50 Euros	R105 300.00 Or \$8100.00 USD Or 6 581.25 Euros	R44 135.00 Or \$3395.00 USD Or 2 758.44 Euros	R47 920.00 Or \$3 686.15 USD Or 2995.00 Euros
Operating Cost (energy, consumables and parts)	Energy consumption: - 1.4kWh/m ³ Maintenance costs: - Cleaning required every 12 months, R1000 to R1500 per clean. Replacement costs: - suction and back flush pumps replaced after 4 yrs. - membrane must be replaced after 10 yrs. - Total replacement costs of R3050/year.	Energy consumption: - 3.81 kWh/m ³ (79.3 Watts over 24 hours) Maintenance: - Cleaning required every 12 months. Cost per clean not provided. Replacement costs: - UV lamp replaced after 12 months. - blower diaphragms replaced after 2 years. - Total replacement costs of R867/year.	Energy consumption: - 0.55 kWh/m ³ (40kWh over 365 days, or \$4.00 worth of electricity per year at 10¢ per kWh) Maintenance: - Cleaning required every 12 months. Cost per clean not provided. Replacement costs: - If the filter screen is compromised, the pump inline strainer may need replacing - Total replacement costs of R65/year.	Energy consumption: - 0.69kWh/m ³ . (110kWh per annum) Maintenance: - Cleaning required every 12 months. Cost per clean not provided. Replacement costs: - Water pump replaced every 4 yrs - Changing of UV lamp every 12 months. - Total replacement costs R360/year.

Indicator	AQUALOOP 300	Aqua2Use GWTS 500	RECOVER®	HYDRALOOP
Dimensions	Footprint: - 1.08m ² Height: - 1.245m	Footprint: - 0.78m ² Height: - 1.332m (+ 0.5m with control box and pumps)	Footprint: - 0.27 m ² Height: - 1.55m	Footprint: - 0.27 m ² Height: - 1.85 m
Mobility	Permanently fixed (The device is connected to household plumbing. The air blowers and control unit are then permanently fixed to an adjacent wall.)	Permanently fixed (The device is connected to household plumbing. The air blowers and control unit are then permanently fixed to an adjacent wall.)	Permanently fixed (The treatment system is connected to household plumbing. All components are contained within the treatment unit.)	Permanently fixed (The treatment system is connected to household plumbing. All components are contained within the treatment unit.)
Total daily treatment capacity	300L per day Or 0.28 m/d	500L per day Or 0.64 m/d	200L per day Or 0.74 m/d	440L per day Or 1.62 m/d

4.2 Suitability of existing technologies to the CoCT urban consumer

4.2.1 Treated water quality

Table 23: Comparison of effluent water quality for existing commercial technologies, including their water quality score (w_o)

Parameter	Effluent Compliance Value	Unit	AQUALOOP	Aqua2Use	RECOVER ¹⁶	HYDRALOOP
COD (or BOD₅)¹⁷	≤30 (≤15)	mg O ₂ / l	10 (5)	<6 (<3)	>20 (>10)	<20 (<10)
TSS	≤10	mg / l	2	<2	>10	<10
E. Coli	<1	CFU / 100ml	<1	<1	<1	<1
Turbidity	<5	NTU	0.57	0.47	>50	<5
pH	6.0-9.0	-	7.38	7.9	6.5-8	6.0-9.0
w_o	-	-	1	1	0.2	1

¹⁶ As no treatment, other than Chlorination, is provided by the RECOVER Greywater Treatment System, effluent quality (excluding E. Coli content) was taken as being that of the influent water quality (i.e. synthetic greywater as characterised by NSF/ANSI 350).

¹⁷ Using an approximate ratio of COD \approx 2BOD₅ where effluent COD is unavailable

4.2.2 End user acceptability

Each of the aforementioned technologies was evaluated in accordance with the criteria specified in Table 17, including the effluent water quality (Table 23, above). The results of this evaluation are presented in Table 24 (below). The calculation procedure as described in section 3.2.2 is shown for the AQUALOOP 300. For the remaining technologies, only the results are shown in Table 25 (below).

Table 24: AQUALOOP 300 end user acceptability score sheet

Dimension	Dim. Weight, w_x	Drawback weight	Drawbacks	Index Guide	Drawback Score
Technical	0.6	0.225	Unpleasant odour	1 = rarely 0 = regularly	1
		0.1	Deficient aesthetics of water	1 = rarely 0 = regularly	1
		0.225	Floor Space	1 if < 1 m ² 0 if > 1m ²	0
		0.225	Device mobility	1 = Portable 0 = Fixed	0
		0.225	Complexity	1 = simple ¹⁸ 0 = complex ⁹	0
Economic	0.36	0.5	Monthly running costs (incl. replacement cost)	1 = less than 0.5% of monthly household income 0 = greater than 0.5% of monthly household income	0
		0.5	Purchase Price	1 if < 50% monthly salary 0 if > 50% monthly salary	0
Social	0.03	0.4	Behavioural requirements	1 = Little to no behavioral change needed 0 = Major behavioural change needed	1
		0.6	Children surveillance	1 = Little to no behavioral change needed 0 = Major behavioural change needed	1
Institutional	0.01	1	Availability of local technical support ¹⁹	1 = Local technical support readily available 0 = Local technical support not available	1

Considering the weighted technical dimension score presented by the AQUALOOP 300,

¹⁸ If treatment device contains more than 2 electro-mechanical components, it is regarded as being a complex design.

¹⁹ i.e. Within South Africa

$$\begin{aligned} \text{Technical Score} &= 0.6 \times (1 \times 0.225 + 1 \times 0.1 + 0 \times 0.225 + 0 \times 0.225 + 0 \times 0.225) \\ &= 0.195 \end{aligned} \quad (25)$$

Considering the weighted economic score of the AQUALOOP 300,

$$\begin{aligned} \text{Economic Score} &= 0.36 \times (0 \times 0.5 + 0 \times 0.5) \\ &= 0 \end{aligned} \quad (26)$$

Considering the weighted social score of the AQUALOOP 300,

$$\begin{aligned} \text{Social Score} &= 0.03 \times (1 \times 0.4 + 1 \times 0.6) \\ &= 0.03 \end{aligned} \quad (27)$$

Considering the weighted institutional score of the AQUALOOP 300,

$$\begin{aligned} \text{Institutional Score} &= 0.01 \times (1 \times 1) \\ &= 0.01 \end{aligned} \quad (28)$$

Thus,

$$\begin{aligned} \beta &= 0.195 + 0 + 0.03 + 0.01 \\ &= 0.235 \end{aligned} \quad (5)$$

Applying Equation 4 for the AQUALOOP 300,

$$A = \frac{w_o + \beta}{2} \quad (4)$$

$$A = \frac{1 + 0.235}{2}$$

$$A = 0.6175 \text{ (or 62\%)}$$

The scoring sheets used to calculate the end user acceptability of the remaining technologies are shown in Annexure B. The results of the calculation for each technology are summarized in the table below.

Table 25: Summary of end user acceptability calculated for each of the commercial technologies considered.

Dimension	Technology	Weighted Dimension Score			
		AQUALOOP 300	Aqua2Use GWTS 500	RECOVER	HYDRALOOP
Technical		0.195	0.33	0.27	0.33
Economic		0.00	0.00	0.18	0.18
Social		0.03	0.03	0.03	0.03
Institutional		0.01	0.00	0.00	0.00
β		0.235	0.36	0.48	0.54
w_o		1.00	1.00	0.2	1.00
<i>End-user acceptability, A</i>		62%	68%	34%	77%

4.2.3 Financial feasibility

An economic feasibility analysis, using the parameters shown in Table 26 and Table 27 (below), was performed for each technology by determining the Net Present Value (Equation 3). Any savings in municipal water were considered as a positive cash flow over the life of the treatment device.

Table 26: Raw input parameters required to determine the financial feasibility of each of the commercial technologies considered

Parameter	Unit	AQUALOOP 300	Aqua2Use GWTS 500	RECOVER	HYDRALOOP
Treatment device purchase price	Rands	65,000	105,300*	44,135*	47,920**
Vol. of treated effluent produced	Litres/Day	300	500	200	440
Energy consumption ²⁰	kWh/m ³	1.40	3.81	0.55	0.69
Maintenance cost ²⁰	Rands/month	104.17	104.17	104.17	104.17
Consumables cost ²⁰	Rands/month	0.00	0.00	40.00	0.00
Replacement cost ²⁰	Rands/month	254.17	72.22	5.42	30
Electricity tariff ²¹	c/kWh	192.8	192.8	192.8	192.8
Days per month	Days	30	30	30	30
Discharge/Supply	-	0.6	0.6	0.6	0.6
Product lifetime	Years	15	15	15	15
Desired rate of return	%	0.01	0.01	0.01	0.01
Inflation, <i>I</i>	%	5.5	5.5	5.5	5.5
Risk Premium	%	2	2	2	2

* Exchange rate R13.00 to \$1.00 USD. ** Exchange rate R16.00 to 1.00 Euro.

²⁰ Refer to Annexure C for a detailed explanation of how these costs were calculated

²¹ Domestic tariff threshold = 600kWh (City of Cape Town, 2018b)

To obtain the appropriate water tariff, the City of Cape Town's Level 4 water restrictions were considered (City of Cape Town, 2017). The total daily treatment capacity of the device was used to determine which tariff step would apply in the feasibility analysis. In the case of the AQUALOOP 300, producing treated effluent at 300L/Day would equate to a municipal saving of 9kL a month, which lies between 6kL and 10.5kL a month. Thus a "Step 2" water tariff (for the domestic non-indignant class) would apply in determining the municipal water (i.e. supply) savings the user would incur when using the AQUALOOP 300. Similarly, for the determination of the sanitation savings, 60% of the users municipal demand of 9kL would ordinarily be expected to be returned to the sewer (Van Zyl et al., 2007). Thus, a sanitary flow of 5.40kL a month could be expected. This figure falls in between 4.2kL and 7.35kL per month. Hence, a "Step 2" sanitation tariff (for domestic non-indigent use) was considered appropriate for the AQUALOOP 300 (City of Cape Town, 2017). In this way, the appropriate water and sanitation tariffs (for the domestic non-indignant class) were applied to each of the technologies considered (City of Cape Town, 2017). The results of this exercise are summarised in Table 27 (below).

A product life time of 15 years was appropriate, as it is typical for decentralised water treatment plants. Also, as the majority of components are non-metallic and are replaceable, a lifetime of 15 years is not unrealistic.

Given that municipal water tariffs are low, it cannot be expected that the treatment device will allow for a large positive NPV at the end of its life, as the intended purpose of the device is to save water as opposed to generate profit. Hence, a desired rate of return of 0.01% was appropriate for this study. The average inflation rate for the last 5 years was utilised for the analysis of all commercial technologies considered (TRADING ECONOMICS, 2018). A risk premium of 2% was selected for all commercial technologies considered (Vertical Spaces Properties, 2018). The sum of the risk premium, inflation rate and desired rate of return provided the *Discount Rate, i* , which is required for the calculation of the NPV (Vertical Spaces Properties, 2018).

Total running costs were calculated by a summation of the maintenance, consumables and replacement cost, together with the monthly energy cost. The reader is referred to Annexure C for a detailed explanation of how these costs were calculated.

Table 27: Calculated input parameters required to determine the financial feasibility of each of the commercial technologies considered

Calculated Parameter	Unit	AQUALOOP	Aqua2Use	RECOVER	HYDRALOOP
Municipal water supply saved	kL/month	9.00	15.00	6.00	13.20
Sanitation discharge saved	kL/month	5.40	9.00	3.60	7.92
Water tariff	R/kL	17.75	25.97	4.56	25.97
Sanitation tariff	R/kL	14.98	30.31	4.39	30.31
Discount rate, i	%	7.51	7.51	7.51	7.51
Water & sanit. savings	R/month	240.64	662.34	43.16	582.86
Total running cost	R/month	382.63	286.47	155.92	137.22
Nett Cash Inflow (R_0)	R/month	-141.98	375.87	-112.76	431.13

The final stage in the feasibility analysis is the calculation of the NPV using the data tabulated above. Calculations performed for the AQUALOOP 300 are shown below, with only the calculation results shown for the remaining technologies.

To determine the operating cash flow for each year over the life time of the treatment device, inflation must be considered. For the case of the AQUALOOP 300, the operational cash flow (R_t), considering inflation, is calculated using Equation 29 (below).

$$R_{t+1} = R_t \times \left(1 + \frac{I}{100}\right) \quad (29)$$

Thus, for year 1 (i.e. the first 12 months),

$$\begin{aligned} R_0 &= -141.98 \times 12 \\ &= -1703.81 \\ R_1 &= R_0 \times \left(1 + \frac{I}{100}\right) \\ &= -1703.81 \times \left(1 + \frac{5.5}{100}\right) \\ &= -1797.52 \text{ Rands} \end{aligned}$$

Equation 29 is applied for all 15 years over which the treatment device is used, providing a Nett Cash Flow for each year. The NPV at the end of the product lifetime can then be calculated as follows.

$$\begin{aligned}
 NPV(7.51\%, 15) &= \sum_{t=0}^{15} \frac{R_t}{(1+i)^t} \\
 &= \frac{-1703.81}{(1+0.0751)^0} + \frac{-1797.52}{(1+0.0751)^1} + \frac{-1896.38}{(1+0.0751)^2} + \dots + \frac{-3803.71}{(1+0.0751)^{15}} \\
 &= -23752.56 \text{ Rands}
 \end{aligned}
 \tag{3}$$

Considering the initial investment made in the purchase of the treatment device,

$$\begin{aligned}
 NPV(7.51\%, 15) &= \sum_{t=0}^{15} \frac{R_t}{(1+i)^t} - \text{Initial Investment} \\
 &= -23\,752.56 - 65\,000.00 \\
 &= -88\,752.56 \text{ Rands}
 \end{aligned}$$

The calculation results for the AQUALOOP 300 and the remaining technological solutions are summarised in Table 28 (below). To view the calculated results for each of the technologies, the reader is referred to Annexure C, Tables 37 to 41.

Table 28: Summary of NPVs calculated for each of the commercial technologies considered

Treatment device	CAPEX (Rands)	NPV (Rands)
AQUALOOP 300	65 000.00	-88 752.56
Aqua2Use GWTS 500	105 300.00	-42 420.62
RECOVER [®]	44 134.00	-62 998.30
HYDRALOOP R	47 920.00	24 204.22

4.3 A novel technical solution

4.3.1 Treated water quality

The water quality produced by the prototype design is expected to be as described in Table 29 (below), achieving compliance with regards to all effluent water quality parameters.

Table 29: Effluent water quality expected to be produced when using the prototype design shown in Figure 20.

Potential End Use	Parameter	Effluent Compliance Value	Unit
Sanitary flushing Laundry use Vehicle washing External surface wash	COD	≤30	mg O ₂ / l
	TSS	≤10	mg / l
	E. Coli	<1	CFU / 100ml
	Turbidity	<5	NTU
	pH	6.0-9.0	-

4.3.2 End user acceptability

The prototype design was evaluated in the same way as the existing commercial technologies considered in this thesis, the relevant design features of which are summarized in Table 30 (below).

Table 30: Summary of prototype design features

Indicator	Prototype design
Extent of direct contact with untreated greywater	Manual feeding of greywater may be performed by the end-user, if required. Manual cleaning of internals carried out every 365 days (i.e. once a year). Manual cleaning of the nylon sock must be carried out on bi-monthly basis. Pre-treated greywater may be extracted by the end user if desired (eg. for toilet flushing)
Unpleasant odours	Unpleasant odours are rarely emitted, as aeration is provided in a sealed vessel.
Tertiary filtration	String wound or polypropylene based cartridge filters for the removal of suspended solids provide the most cost-effective solution. However, Polypropylene based filters with an ability to resist biological fouling will provide superior results. Given the modular design of the prototype, these can easily be changed as and when required by the end user.
Tertiary disinfection	Tertiary disinfection provided either by chemical disinfection after extraction by the end user, or by UV-C disinfection in the treated water chamber (i.e. chamber 4, Figure 20).
Degree of human intervention in its operation	The device is manually operated. The user collects his/her greywater into a storage container. This can be done by either custom plumbing or through manual collection. The greywater is then supplied to the treatment device in one of two ways: (i) Greywater from the storage container is strained manually and then poured into the top of the treatment device (i.e. chamber 1, Figure 20), with the cap of the treatment device removed and the overflow pipe in the first chamber of the treatment device directed to a sanitary drain, or (ii) Greywater from the storage container is pumped into the top of the treatment device (using a small submersible pump),

	<p>easily connected using a standard 12mm hose and quick release coupling. The overflow pipe in the first chamber of the treatment device is directed back into the storage container.</p> <p>Sludge is wasted from the sludge waste tap (see Figure 20), either by (i) opening the tap on a regular basis for a prescribed duration and wasting of the mixed liquor directly or indirectly into the drain, or (ii) by having the sludge waste tap permanently left open at a prescribed set point (allowing for a fixed and continuous waste flow) and remaining permanently connected to a sanitary drain.</p> <p>Treated greywater is then extracted (into a container) by the end user by opening the valve at the bottom of the treatment device.</p>
Electro-mechanical components	Electro-mechanical components include a linear diaphragm air pump (Annexure E), which provides air for biological treatment and sludge recirculation.
Purchase Price (excluding taxes)	Purchase Price estimated to be R16 055.00 ²²
Operating Cost (energy, consumables and parts)	<p>Energy consumption – 0.88kWh/m³, with the treatment device making use of an 8.5W HIBLOW CD-8S Diaphragm Air Pump. The pump is expected to last for at least 7 years before needing replacement, at an estimated cost of R1000. If a UV lamp is also chosen, energy consumption per m³ will increase substantially²³.</p> <p>It is envisaged that replacement of the four filtration elements will be required every 6 months, which can be done by the end user, at an estimated cost of R100 per filter.</p>
Dimensions	Treatment device diameter footprint 0.26m ² , 1556mm height.
Mobility	The device does not need to be connected to household plumbing. It is however advisable that the overflow line and the sludge waste tap are permanently connected to a drainage point. When placed on a movable base, the device becomes fully portable (save for the electrical supply).
Total daily treatment capacity	249L per day, or 0.96 m/d, producing 232L per day of treated greywater.

As was done for the existing commercial technologies considered, the end user acceptability of the prototype design was evaluated in accordance with the criteria specified in Table 17. The result of this analysis is presented in Table 31 (below).

²² Refer to Annexure D for a Bill of Materials including the (estimated) cost breakdown of the prototype design.

²³ Only the costs resulting from a prototype design relying upon manual chemical disinfection were considered. Furthermore, only a manually loaded prototype design was considered, as any additional costs regarding storage and distribution are user dependent and site specific.

Table 31: Prototype design end user acceptability score sheet

Technology Name: Prototype

Dimension	Dim. Weight, w_x	Drawback weight	Drawbacks	Index Guide	Drawback Score
Technical	0.6	0.225	Unpleasant odour	1 = rarely 0 = regularly	1
		0.1	Deficient aesthetics of water	1 = rarely 0 = regularly	1
		0.225	Floor Space	1 if < 1 m ² 0 if > 1m ²	1
		0.225	Device mobility	1 = Portable 0 = Fixed	1
		0.225	Complexity	1 = simple ²⁴ 0 = complex	1
Economic	0.36	0.5	Monthly running costs (incl. replacement cost)	1 = less than 0.5% of monthly household income 0 = greater than 0.5% of monthly household income	1
		0.5	Purchase Price	1 if < 50% monthly salary 0 if > 50% monthly salary	1
Social	0.03	0.4	Behavioural requirements	1 = Little to no behavioral change needed 0 = Major behavioural change needed	0
		0.6	Children surveillance	1 = Little to no behavioral change needed 0 = Major behavioural change needed	0
Institutional	0.01	1	Availability of local technical support ²⁵	1 = Local technical support readily available 0 = Local technical support not available	1
					$\beta = 0.97$

²⁴ If treatment device contains more than 2 electro-mechanical components, it is regarded as being a complex design.

²⁵ i.e. Within South Africa

The end-user acceptability score was calculated in the same way as before, and is shown adjacent to those calculated for the existing commercial technologies in Table 32 (below).

Table 32: Summary of end user acceptability (for the urban CoCT resident) calculated for the prototype design and for each of the commercial technologies considered

Dimension	Technology	Weighted Dimension Score				Prototype
		AQUALOOP 300	Aqua2Use GWTS 500	RECOVER	HYDRALOOP	
Technical		0.195	0.33	0.27	0.33	0.6
Economic		0.00	0.00	0.18	0.18	0.36
Social		0.03	0.03	0.03	0.03	0.00
Institutional		0.01	0.00	0.00	0.00	0.01
β		0.235	0.36	0.48	0.54	0.97
w_o		1.00	1.00	0.2	1.00	1.00
<i>End-user acceptability, A</i>		62%	68%	34%	77%	98.5%

4.3.3 Financial feasibility

An economic feasibility analysis was performed in the same way as was done for each commercial technology, determining the Net Present Value (Equation 3) using the input parameters shown in Table 33 and Table 34 (below). Any savings in municipal water were considered as a positive cash flow over the life of the treatment device.

Table 33: Raw input parameters required to determine the financial feasibility of the prototype design

Parameter	Unit	Prototype Design
Treatment device purchase price ²⁶	Rands	16 055
Vol. of treated effluent produced	Litres/Day	232
Energy consumption	kWh/m ³	0.88
Maintenance cost (See Annex C)	Rands/month	0.00
Consumables cost (See Annex C)	Rands/month	26.00
Replacement cost (See Annex C)	Rands/month	78.41
Electricity tariff ²⁷	c/kWh	192.8
Days per month	Days	30
Discharge/Supply ratio	-	0.6
Product lifetime	Years	15
Desired rate of return	%	0.01
Inflation, <i>I</i>	%	5.5
Risk Premium	%	2

²⁶ See Annexure D

²⁷ Domestic tariff threshold = 600kWh (City of Cape Town, 2018b)

To obtain the appropriate water tariff, the City of Cape Town’s Level 4 water restrictions were considered (City of Cape Town, 2017), as was done for the existing commercial technologies. Similarly, for the determination of the sanitation savings, 60% of the users municipal demand would ordinarily be expected to be returned to the sewer (Van Zyl et al., 2007). The results of this exercise are summarised in Table 34 (below).

A product life time of 15 years was appropriate, as the prototype design makes use of predominantly non-metallic components. Many of these components are also available as off-the-shelf items. Any metallic components which are in contact with the water, such as the cylindrical sections, are coated with an elastomeric polyurethane coating to prevent corrosion.

Table 34: Calculated input parameters required to determine the financial feasibility of the prototype design

Calculated Parameter	Unit	Prototype design
Municipal water supply saving	kL/month	6.96
Sanitation discharge saving	kL/month	4.18
Water tariff	Rands/kL	17.75
Sanitation tariff	Rands/kL	14.98
Discount rate	%	7.51
Water & sanit. savings	Rands/month	186.10
Total running cost	Rands/month	116.21
Nett Cash Inflow	Rands/month	69.89

In the same way as was done for each of the existing commercial technologies considered in this study, the NPV of the prototype design (using the data tabulated above) was calculated, the results of which are shown in Table 35 (below). A detailed breakdown of costs calculated for each year is provided in Annexure C, Table 41.

Table 35: Summary of NPVs calculated for each of the commercial technologies considered, together with that of the prototype design, when considering Level 4 water restrictions in the City of Cape Town

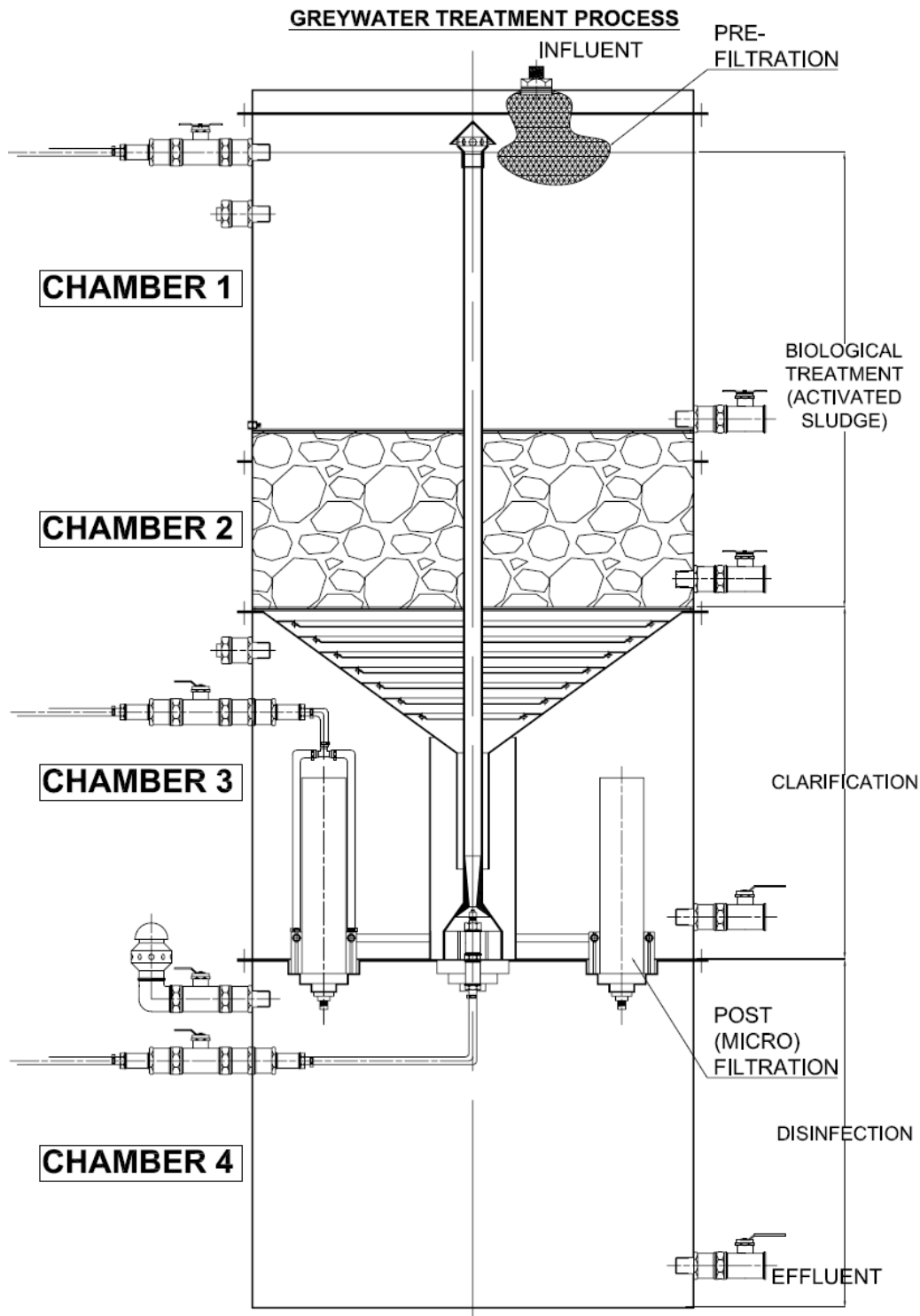
Treatment device	CAPEX (Rands)	NPV (Rands)
AQUALOOP 300	65 000.00	-88 752.56
Aqua2Use GWTS 500	105 300.00	-42 420.62
RECOVER [®]	44 134.00	-62 998.30
HYDRALOOP R	47 920.00	24 204.22
Prototype Design	16 055.00	-4 363.29

4.3.4 Summary of proposed invention

According to the invention (shown in Figure 27, below) there is a compact greywater recycler (with a treatment capacity of approximately 249 litres per day, producing 232 litres per day) including:

- a greywater chamber, with cap, for the pre-screening of greywater, and fittings to provide a means for the quick connection of a pumped greywater supply
- a greywater chamber, for the holding of pre-filtered greywater, aeration and the receiving of recirculated biological sludge
- tensioned mesh screen and frame
- an attached growth chamber, for the housing of attached growth media to facilitate and promote bacteriological growth and COD reduction
- a conical, ribbed section at the base of the attached growth chamber to allow for (i) the infiltration of air provided from the chamber beneath, and (ii) the conveyance of suspended solids into a baffled chamber to promote settling
- a baffled chamber to (i) collect solid particulates which have dropped out of suspension, (ii) house a Venturi pump to recirculate settled particulates (i.e. sludge) into the pre-filtered greywater receiving chamber, (iii) house gravity filtration media, (iv) prevent suspended particulates from reaching the filtration media, and (v) to facilitate the injection of air for aeration and sludge conveyance
- a sludge conveyor, operating as a Venturi pump, for the recirculation of sludge into the pre-filtered greywater receiving chamber
- fittings to facilitate the connection of a compressed air supply for air delivery (used for aeration and sludge conveyance)
- a clean water storage chamber, for the disinfection (UV-C), if desired, and storage of treated greywater
- a “sludge waste tap” for the hydraulic control of sludge age (wasting from Chambers 1 or 2)
- gaskets and fasteners for the joining of each of the chambers to form a vertical, solid, water-tight vessel
- backing nut tank accessories, unions, isolation valves, 90° elbows, barbed hose fittings, hose clamps, O-rings, and hose for delivery of air and the extraction of water from each of the chambers
- backing nut tank accessories, unions, isolation valves, 90° elbows, barbed hose fittings, hose clamps, O-rings, and hose to allow for overflow into a municipal drain and to prevent vacuum formation within each chamber

The invention is designed such that it requires little to no expertise to assemble and operate. The large constituent of off-the-shelf components allows for easy maintenance of the invention. It is cylindrical in shape and stands vertically, designed to accommodate the treatment of greywater in areas where space is limited.



PARAMETER	INFLUENT	EFFLUENT	UNIT
COD	260-360	20	mgCOD/l
TSS	80-160	<10	mgTSS/l
E. COLI	10^2-10^3	<1	CFU/100ml
TURBIDITY	50-100	<5	NTU
pH	6.5-8.0	6.5-8.0	-

Figure 27: Overview of the greywater treatment process and influent and effluent qualities for the proposed technical solution, treating 249 litres per day

5. Discussion of Results

5.1 Summary of results

Several commercial technologies exist to aid consumers in reducing their municipal water demand through greywater recycling. The smallest treatment device considered, in terms of treatment capacity, is able to treat 200 litres of household greywater per day. The largest treatment device considered has a treatment capacity of 500 litres per day. When considering that the illustrative middle-income household (as defined in Table 15) is expected to produce 222 to 444 litres of greywater per day in the absence of extreme weather phenomena (specifically drought), two of the four commercial technologies, the Aqua2Use GWTS 500 and the HYDRALOOP R, are able to provide the greywater treatment capacity needed by the household housing 2 to 4 occupants. Under drought conditions, the household is expected to produce 128 to 256 litres of greywater per day. In such instances all commercial technologies, excluding the RECOVER treatment device, are able to provide the greywater treatment capacity needed by the household housing 2 to 4 occupants.

When considering the specific treatment capacity (i.e. cubic metres of greywater treated per day per square metre of floor space, or metres per day) of each device, the HYDRALOOP R is far superior, with a specific treatment capacity more than double all other commercial technologies. Thus, the HYDRALOOP R design is the most appropriate existing commercial technology for the illustrative household when considering the maximum treatment capacity required by the household. The proposed technical solution, having the second highest specific treatment capacity (0.96m/d) of all solutions, is only able to treat 249 litres of greywater per day. In the absence of drought, the proposed device is only capable of meeting the demand (with regards to treatment capacity) of the illustrative household containing 2 occupants. It is only under drought conditions that the proposed device is expected to meet the demand of the illustrative household containing 4 occupants.

All of the existing commercial treatment devices considered limit direct human contact with untreated greywater. Contact will only occur in the event of maintenance activities, such as the cleaning of filters; the primary reason for this being that these devices are permanently fixed within the household and are connected to greywater sources by means of household plumbing. The proposed technical solution increases the amount of direct human contact with untreated greywater; the reason being that it may be treated as a portable greywater treatment device which does not need to be permanently connected to greywater sources by household plumbing. The increased amount of contact with untreated greywater may be seen as a drawback by the illustrative household. However, this would be offset by the advantage gained from the device's mobility.

All treatment devices, existing and proposed and excluding the RECOVER treatment device, make use of mechanical aeration. This will prevent the emission of unpleasant odours. Furthermore, only the RECOVER treatment device produces treated water of an unacceptable quality. All other devices produce treated greywater which is regarded as being sterile and of sufficient quality (as per Table 16). Hence, the perceived health risk for the majority of these treatment devices would be low.

The perceived level of complexity for all existing commercial treatment devices is high, all of which make use of several electro-mechanical components, such as pumps, solenoid valves and control panels etc. All of these commercial treatment devices require technical expertise to carry out (annual) maintenance activities. In contrast, the proposed technical solution only makes use of a single electro-mechanical component (being a linear air pump) and would thus not require technical expertise to maintain.

Life-cycle costs, including energy, maintenance, consumables and replacement costs, can vary significantly for the treatment devices, lying between R100 and R400 (or between 0.3 and 1.2 percent of the illustrative household's monthly income). The proposed technical solution offers the lowest life-cycle cost, estimated at R116 per month, whilst the HYDRALOOP R offers the second lowest life-cycle cost, estimated at R151 per month. This is attributed to their low energy consumption and their low replacement cost. The Aqualoop treatment device has the highest life-cycle cost, due to the high cost of components which will need replacing.

When evaluating the Net Present Value (NPV) of each of the treatment devices, including the proposed technical solution, the HYDRALOOP R holds the highest NPV with a positive NPV of approximately R24 204; the primary reason for this being that it is able to allow for large savings in municipal water, with little operational expenditure. The proposed technical solution offers the second highest NPV, with a negative NPV of approximately R4 363. Although the proposed technical solution has the lowest life-cycle cost with an estimated purchase price equal to only a third of the HYDRALOOP R's purchase price, the amount of water saved through the use of the proposed device is approximately 40% less than through the use of the HYDRALOOP R. These are the primary reasons for the proposed technical solution resulting in a negative NPV. All other treatment devices result in a negative NPV at least ten times greater than that of the proposed technical solution due to their high life-cycle cost and high purchase price.

All commercial and proposed treatment devices considered, excluding the AQUALOOP 300, occupy a floor space smaller than 1m². All existing commercial devices also require permanent installation. It is only the proposed technical solution which does not require permanent installation, making it ideal for the illustrative household which does not own the property on which they reside.

In the design of the proposed technical solution, it was observed that the greywater being treated may be deficient in the nutrients (TKN and TP) needed to sustain a biological treatment process. This was also noted in research undertaken by several authors already discussed in the literature review. Thus, any household which makes use of the proposed design will need to ensure that they only use cleaning agents and detergents which stimulate and provide the nutrition required for biological treatment. Furthermore, one is uncertain as to whether or not it is indeed a biological process which drives the treatment of the greywater in the existing commercial treatment devices currently on the market.

5.2 Suitability of existing technologies to the CoCT urban consumer

5.2.1 Treated water quality

Three of the four treatment devices, the AQUALOOP 300, the Aqua2Use GWTS 500, and the HYDRALOOP R provide treated greywater at a quality which complies with all of the requirements specified in Table 16.

The RECOVER® greywater treatment system produces treated greywater of the poorest quality. However, the treated water produced should still comply with the sterility requirements (i.e. E. Coli <1 MPU/100ml) of Table 16, as it is regularly dosed with Chlorine. This still ensures that the treated greywater is fit for toilet flushing, which is the intended purpose of the RECOVER® greywater treatment system.

When considering treated water quality, the AQUALOOP 300, the Aqua2Use GWTS 500 and the HYDRALOOP R will have a high level of public acceptance. Considering the preceding literature study, the reasons for this are as follows:

- The treated water produced is not aesthetically offensive (i.e. it is clear and odourless).
- The treated water can be regarded as sterile, presenting a low perceived health risk.
- There is very little to no direct contact between the user and the untreated greywater.

However, when considering that the perceived health risk is reduced when some level of tertiary filtration is provided, the AQUALOOP 300 and the Aqua2Use GWTS 500 is expected to have a greater level of public acceptance (Po et al., 2003).

Despite the fact that the RECOVER® greywater treatment system produces treated greywater which only meets treated water quality requirements when considering sterility, it too would receive a large amount of public acceptance, as the water produced is only used in applications deemed acceptable by the public (i.e. toilet flushing).

5.2.2 End user acceptability

Considering the end user acceptability scores for each of the commercial technologies, it is observed that most present a low health risk, as all make use of tertiary filtration and/or disinfection. The perceived complexity of all the treatment devices is also moderate to high, as each of the designs utilise several electro-mechanical components and electronic user interfaces.

When considering the amount of floor space occupied by each of the treatment devices, the RECOVER® greywater treatment system and the HYDRALOOP R occupy the least amount of floor space. When considering daily treatment capacity, only the Aqua2Use GWTS 500 and the

HYDRALOOP R greywater treatment systems are appropriately sized to meet the needs of the illustrative middle-income household as defined in this study.

The device seen as having the greatest end user acceptability (out of all of those considered), is the HYDRALOOP R. The reasons being that (i) the quality of treated greywater is high, presenting a very low (perceived) health risk (i.e. no unpleasant odours, no deficiency in aesthetics, and a footprint of less than 1m²), and that (ii) the life-cycle cost is very low. However, the treatment device, like all the others considered, is not portable and would be seen as a permanent fixture in any household. It also requires a capital investment which is greater than 50% of the illustrative household's average monthly income.

Although the end user acceptability of three of the four commercial technologies considered is above 50%, there is no single treatment device which can offer a complete solution within the constraints of the illustrative middle-income household (as defined in Table 15).

5.2.3 Financial feasibility

The Net Present Value (NPV) of each commercial technology was calculated over a period of 15 years (deemed an acceptable product lifetime). The results of this calculation indicated that three of the four commercial technologies considered result in a negative NPV at the end of their lifetime, implying that they are not financially feasible solutions.

The treatment device which resulted in a positive NPV at the end of its life was the HYDRALOOP greywater treatment system, implying that it is a financially feasible solution for the end-user; the primary reason for this being that it is able to allow for large savings in municipal water, with little operational expenditure. However, given that the capital investment needed is 40% greater than the illustrative household's maximum monthly income, a sound environmental consciousness and a long term financial commitment would be necessary.

5.2.4 Conclusion

An assessment of the treated water quality, the end user acceptability and the financial feasibility of each treatment device was performed. These analyses indicate that each treatment device satisfies some, but not all, constraints defined for the illustrative middle-income household in the City of Cape Town. For instance, the treatment device may produce treated water of a high quality, in line with the requirements specified in Table 16. However, the same device may not be portable or financially feasible for the household. All commercial treatment devices considered in this study require a capital investment which is greater than the maximum monthly income of the illustrative household in the City of Cape Town. Hence, there is no single treatment device which can offer a complete solution within the constraints of the illustrative household.

5.3 A novel technical solution

5.3.1 Treated water quality

The proposed design is able to treat approximately 249 litres of greywater per day, producing 232 litres of treated water. The quality of the treated water produced by the proposed prototype design is expected to satisfy all criteria deemed appropriate for sanitary flushing, laundry use, vehicle washing and surface cleaning.

5.3.2 End user acceptability

In comparison to the existing commercial technologies considered for the purposes of this study, the proposed prototype design should have a higher end user acceptability when considering the constraints of the middle-income household in the City of Cape Town; the primary reasons for its increased level of acceptance being its purchase price, simplicity and mobility.

5.3.3 Financial feasibility

The financial feasibility analysis of the prototype design produced a negative NPV. However, in comparison to the other existing commercial technologies considered, the prototype offers the lowest life-cycle cost per month (which includes energy, maintenance, consumables and replacement costs).

Hence, when considering the needs of the illustrative middle-income household in the City of Cape Town, the proposed prototype may be seen as an appropriate solution; the reasons for this being that (i) the purchase price is estimated to be equal to approximately 50% of the household's maximum monthly income, (ii) the life-cycle cost is low, constituting 0.4 percent of the households maximum monthly income, (iii) the floor space occupied by the prototype is under 1m², and (iv) the prototype is fully portable. These factors make it more likely that the illustrative household will purchase the treatment device, but only if the intention of the household is not to make a profit through water savings, but to practice greywater recycling to the greatest extent possible. Furthermore, given the very low monetary value of water, it makes it very difficult for any treatment device of this size to achieve a positive NPV and can be seen as a practical limitation for any such design (until such time that the true value of water is factored into the monetary value of water charged to the consumer).

Given that the capital investment required for the prototype design does not consider economies of scale, the capital investment required may very well be reduced if the treatment device is mass-produced. This would of course influence the resulting NPV significantly.

5.3.4 Conclusion

The proposed prototype is capable of treating approximately 249L of greywater per day, within the constraints defined for an illustrative middle-income household in the City of Cape Town. The invention is designed such that it requires little to no expertise to assemble and operate. The large constituent of off-the-shelf components allows for easy maintenance of the invention. It is cylindrical in shape and stands vertically, designed to accommodate the treatment of greywater in areas where space is limited. Proof of the prototype's novelty lie in the following claims:

1. According to the invention there is a compact greywater recycler including:

- a greywater chamber, with cap, for the pre-screening of greywater, and fittings to provide a means for the quick connection of a pumped greywater supply
- a greywater chamber, for the holding of pre-filtered greywater, aeration and the receiving of recirculated biological sludge
- tensioned mesh screen and frame
- an attached growth chamber, for the housing of attached growth media to facilitate and promote bacteriological growth and BOD reduction
- a conical, ribbed section at the base of the attached growth chamber to allow for (i) the infiltration of air provided from the chamber beneath, and (ii) the conveyance of suspended solids into a baffled chamber to promote settling
- a baffled chamber to (i) collect solid particulates which have dropped out of suspension, (ii) house a Venturi pump to recirculate settled particulates (i.e. sludge) into the pre-filtered greywater receiving chamber, (iii) house gravity filtration media, (iv) prevent solid particulates from reaching the filtration media, and (v) to facilitate the injection of air for aeration and sludge conveyance
- a sludge conveyor, operating as a Venturi pump, for the recirculation of sludge into the pre-filtered greywater receiving chamber
- fittings to facilitate the connection of a diaphragm pump for air delivery (used for aeration and sludge conveyance)
- a clean water storage chamber, for the disinfection (UV-C) and storage of treated greywater
- gaskets and fasteners for the joining of each of the chambers to form a vertical, solid, water-tight vessel
- backing nut tank accessories, unions, isolation valves, 90° elbows, barbed hose fittings, hose clamps, O-rings, and hose for delivery of air and the extraction of water from each of the chambers

- backing nut tank accessories, unions, isolation valves, 90° elbows, barbed hose fittings, hose clamps, O-rings, and hose to allow for overflow into a municipal drain and to prevent vacuum formation within each chamber
2. A compact greywater recycler according to claim 1, wherein the design is of a modular construction using cylindrical sections joined through gaskets and fasteners to ensure a watertight seal.
 3. A compact greywater recycler according to claim 1, wherein a chamber is provided for the provision of a multi-media bed filter (i.e. attached growth chamber).
 4. A compact greywater recycler according to claim 1, wherein an attached growth chamber with a perforated conical section and circumferential baffle ring inserts at its base are used to direct the water into a settling chamber, prior to it being received by the filtration elements.
 5. A compact greywater recycler according to claim 1, wherein an attached growth chamber with a perforated conical section and circumferential baffle ring inserts at its base are used to allow for aeration of the attached growth media, whilst preventing the infiltration of suspended solids towards the filtration elements.
 6. A compact greywater recycler according to claim 1, wherein a Venturi pump and sludge conveyor allow for the recirculation of sludge to the first chamber wherein greywater is received.
 7. A compact greywater recycler according to claim 1, wherein a baffle chamber allows for the vertical insertion of standard 9" filter elements along its circumference
 9. A compact greywater recycler according to claim 1, wherein a chamber is provided at its base for the storing of treated greywater.
 10. A compact greywater recycler according to claim 1, wherein wastewater undergoes prescreening, aeration, treatment, clarification, and filtration within a compact, vertical, tower arrangement of cylindrical segments each containing separate treatment stages.
 11. A compact greywater recycler according to claim 1, wherein wastewater flows through several stages of prescreening, treatment and filtration by means of gravity only.
 12. A compact greywater recycler according to claim 1, wherein provision is made for either manual or pumped greywater supply.



13. A compact greywater recycler according to claim 1, wherein provision is made for the extraction of water at various stages of the greywater recycling process, in accordance with the needs of the user.

14. A compact greywater recycler according to claim 1, wherein provision is made for complete customization of the pre-screening, aeration, treatment, clarification and filtration stages to suit user requirements.

6. Conclusion

South Africa is classified as being the 30th driest country in the world and is regarded as a water scarce country. However, for the urban residents of the City of Cape Town, the ability to reduce their municipal water consumption through initiatives, other than simply using less water, is limited. Hence, there is a need for affordable, simple and compact technical solutions which allow urban populations residing in high density developments to make use of alternative sources of water, with greywater being the most appropriate source to reduce their municipal water demand.

Existing commercial technologies were considered, together with the socio-economic and technical constraints of an illustrative middle-income household in the City of Cape (CoCT). Most technologies considered were expected to have a high level of public acceptance. Out of the four existing commercial technologies considered, only the HYDRALOOP R was seen as being a financially feasible solution, resulting in a positive net present value (NPV) when considering all life-cycle costs. Following the evaluation of each of the commercial technologies considered in this thesis, it was found that each commercial technology satisfied some, but not all, constraints characteristic of the middle-income household in the City of Cape; the primary reasons being their purchase price and lack of mobility.

The proposed greywater treatment device consists of four cylindrical chambers in a vertical arrangement. Raw greywater enters the top chamber and treated greywater is extracted from the bottom chamber forming the base. The treatment processes undergone as the greywater flows through the treatment device include, in the following order, pre-filtration, biological treatment (Activated Sludge), clarification, filtration and disinfection. The process is driven by a combination of gravity and electrical energy.

The proposed design was shown to be capable of treating 249 litres of greywater per day, producing 232 litres of treated greywater fit for indoor surface cleaning, vehicle washing and laundry. In the absence of water restrictions, the treatment capacity provided is only suitable for the illustrative middle-income household containing 2 occupants. It is only under drought conditions where the treatment capacity of the proposed design is sufficient for the illustrative household containing 4 occupants.

Calculations have shown that the low influent nitrogen (i.e. TKN) and phosphorus (i.e. TP) concentrations may limit the biological processes governing the treatment of the greywater. Given these low TKN and TP concentrations in the untreated greywater, any household which makes use of the proposed design will need to ensure that they only use cleaning agents and detergents that

provide the nutrition required for biological treatment. Furthermore, one is uncertain as to whether or not it is a biological process which drives the treatment of the greywater in the existing commercial treatment devices currently on the market. It is for this reason that a high importance must be placed on site-specific greywater characterisation to confirm the appropriateness of any treatment device.

The proposed design is constructed using readily available materials and components. It is modular in its construction, allowing for easy maintenance, assembly and an increase in design flexibility. Evaluating the design against the same evaluation criteria stipulated for the existing commercial technologies showed that the proposed design may be an appropriate solution for the illustrative middle-income household in the City of Cape; the primary reasons for its superiority attributed to its low life-cycle cost, low purchase price and high level of mobility. The most significant drawbacks of the proposed design include (i) its ability to only provide sufficient greywater treatment capacity for the illustrative (4-person) household under drought conditions, and (ii) its negative Net Present Value (NPV) of R4 363.29; the primary reason being that the amount of water saved through the use of the proposed device is low in comparison to existing commercial technologies.

When considering the above, the proposed prototype design may be seen as a novel technical solution. However, due to several assumptions made for the purposes of this minor dissertation, further study (as per the recommendations below) is necessary to validate the performance of the prototype design. For example, the presence of attached growth media is known to increase the treatment capacity of wastewater treatment devices (and thus their Net Present Value). This effect could not be not considered in the design of the prototype due to the scope of this dissertation. Also, economies of scale were not taken into account, which could otherwise significantly reduce the estimated cost of the prototype.

7. Recommendations

Due to the limited scope of this study, several uncertainties exist, such as, *inter alia*, actual wastewater characteristics, sludge settleability and the influence of attached growth media on the biological treatment process. Hence, it is recommended that further study be undertaken, with the scope limited to the construction and testing of the prototype design. These experiments would make use of (completely characterised) household greywater, the results of which can be used to validate or improve the mathematical model and prototype design proposed in this minor dissertation.

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Annexure A – Detailed design drawings of the proposed technical solution

Contents:

- **Figure A-1.1** shows a front view of a compact greywater recycler, according to the present invention;
- **Figure A-1.2** shows a sectioned front view of a compact greywater recycler, according to the present invention;
- **Figure A-1.3** shows a sectioned top view of a compact greywater recycler, according to the present invention;
- **Figure A-1.4** shows a bill of quantities and materials, according to the present invention;
- **Figure A-2** shows a magnified view of the attached growth chamber, according to the present invention;
- **Figure A-3** shows a magnified view of the baffle chamber and the conical section, according to the present invention;
- **Figure A-4** shows a magnified view of the sludge conveyor, according to the present invention;
- **Figure A-5** shows a magnified view of filtration elements housed atop the baffle insert within the baffle chamber, according to the present invention;
- **Figure A-6** shows the expected hydraulic flow pattern, according to the present invention;
- **Figure A-7** shows the internal dimensions of the compact greywater recycler, according to the present invention;

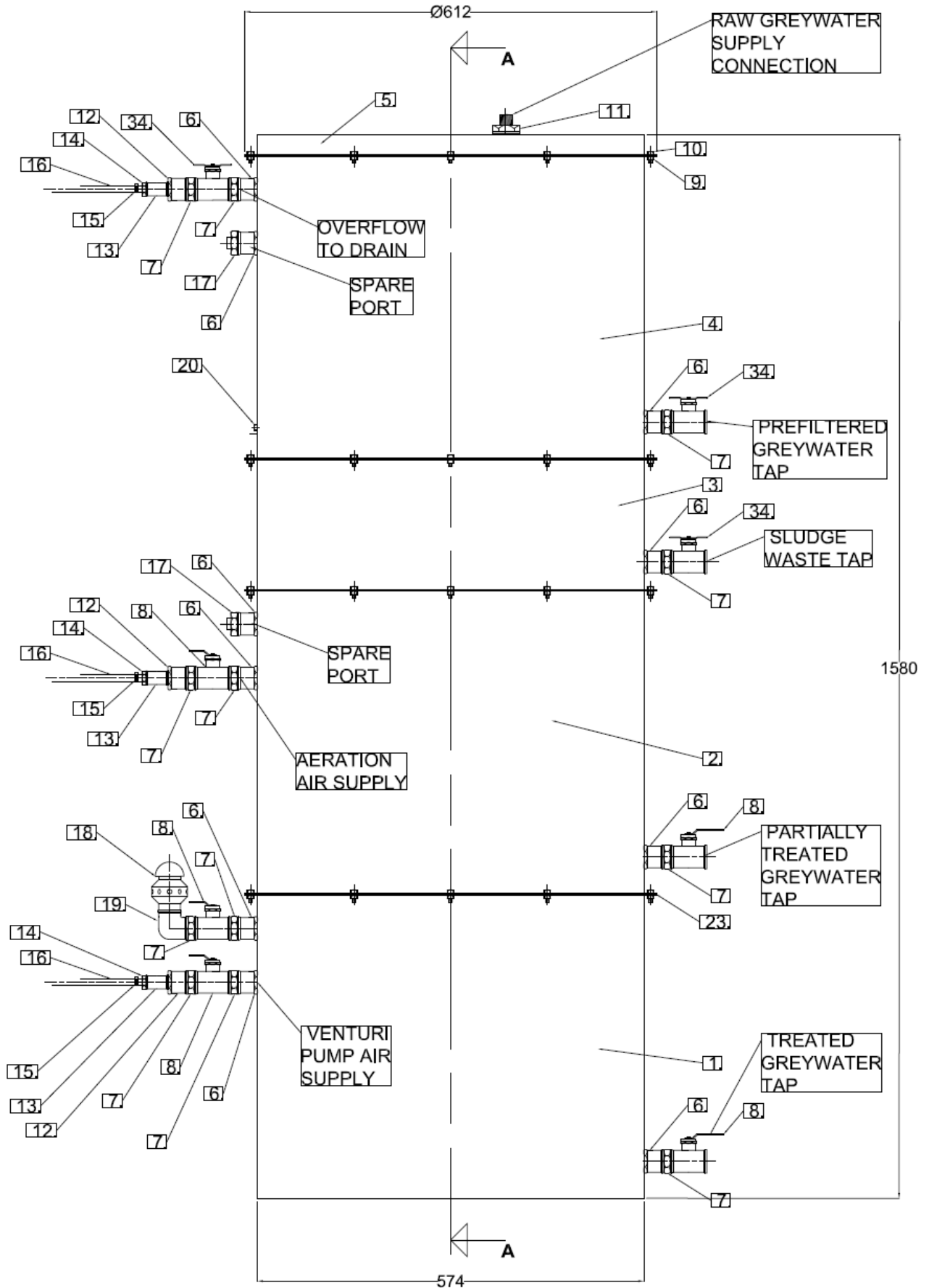


Figure A-1.1: Front view of the proposed technical solution. Refer to the Bill of Materials (Figure A-1.4) for a description of the components numbered herein

SECTION VIEW A-A

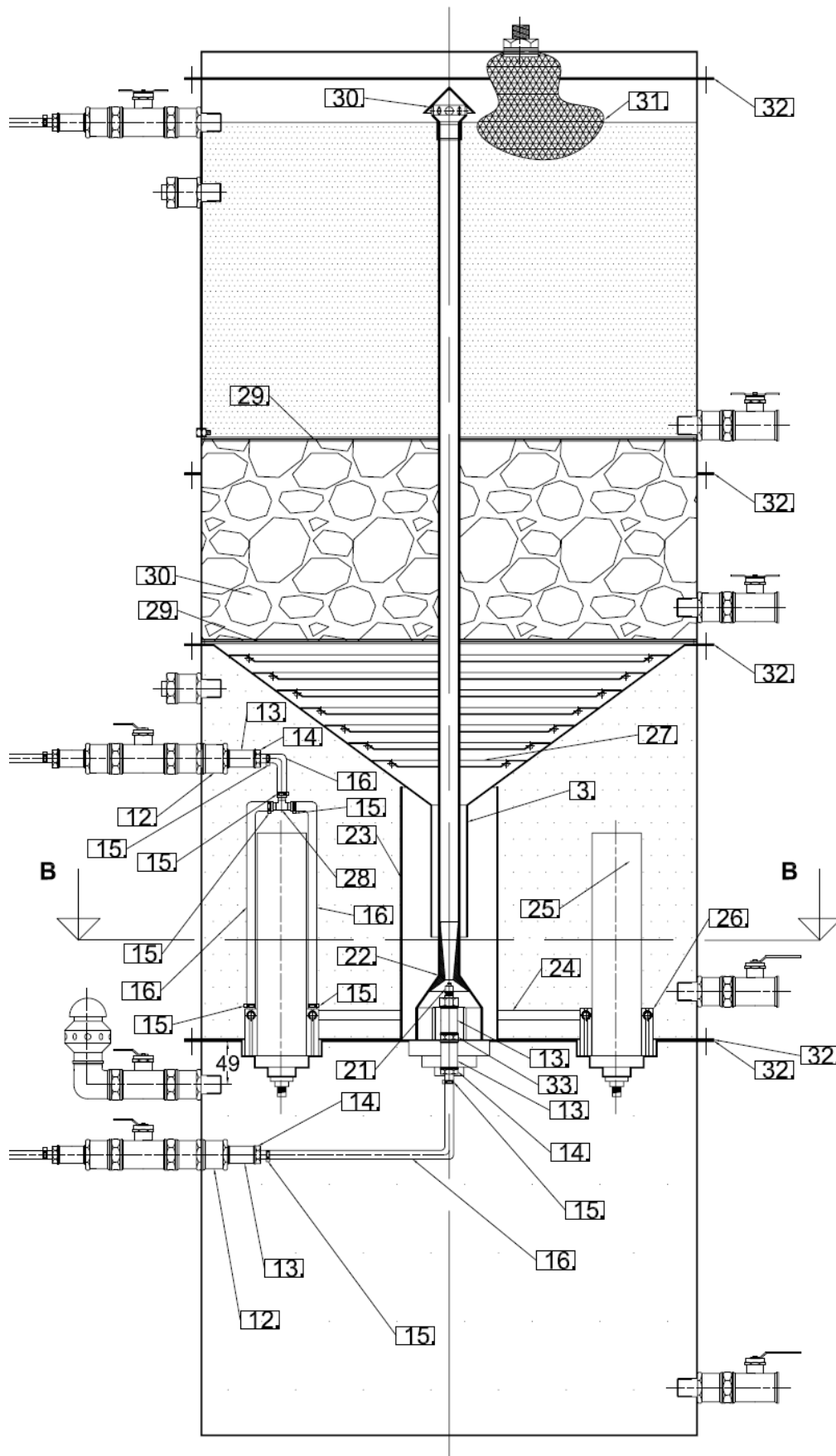


Figure A-1.2: Sectioned view (A-A) of the proposed technical solution. Refer to the Bill of Materials (Figure A-1.4) for a description of the components numbered herein

SECTION VIEW B-B

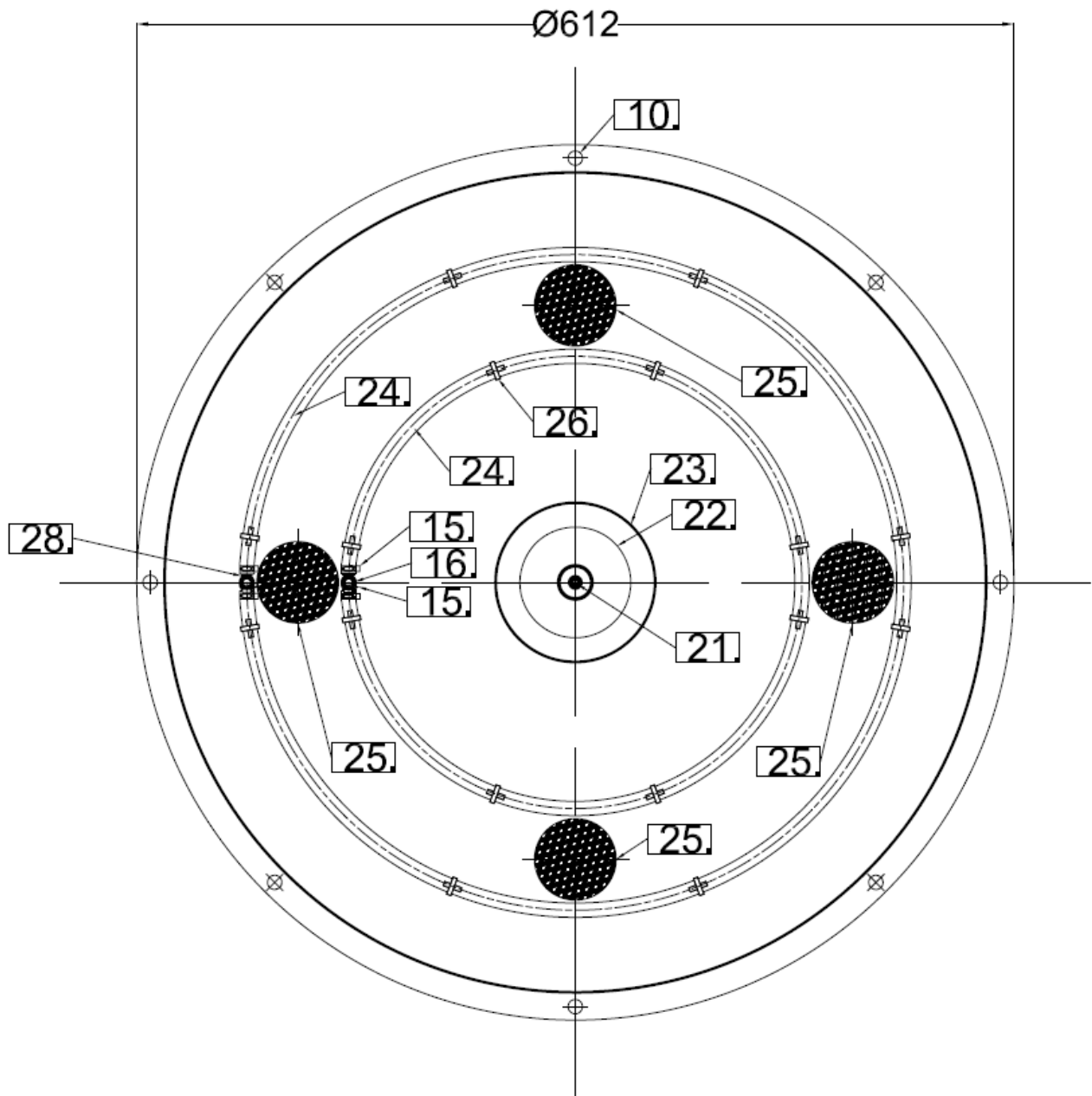


Figure A-1.3: Sectioned view (B-B) of the proposed technical solution. Refer to the Bill of Materials (Figure A-1.4) for a description of the components numbered herein

BILL OF MATERIALS					
ITEM #	QTY	UNIT	DESCRIPTION	MATERIAL	SOURCE
1.	1	PIECES	CLEAN WATER STORAGE CHAMBER - CHAMBER 4	MILD ST. (EPOXY CTD)	CUSTOM
2.	1	PIECES	BAFFLE CHAMBER - CHAMBER 3	MILD ST. (EPOXY CTD)	CUSTOM
3.	1	PIECES	ATTACHED GROWTH CHAMBER - CHAMBER 2	MILD ST. (EPOXY CTD)	CUSTOM
4.	1	PIECES	PRE-FILTERED WATER CHAMBER - CHAMBER 1	MILD ST. (EPOXY CTD)	CUSTOM
5.	1	PIECES	CYLINDRICAL CAP	MILD ST. (EPOXY CTD)	CUSTOM
6.	10	PIECES	3/4" BSP M-F ADAPTER	SS316	SHELF
7.	12	PIECES	3/4" BSP M-M UNION	POLYPROPYLENE	SHELF
8.	5	PIECES	3/4" BSP F-F ISOLATION LEVER BALL VALVE	POLYPROPYLENE	SHELF
9.	32	PIECES	M5 X 20 BOLT	MILD STEEL (GALV.)	SHELF
10.	32	PIECES	M5 NUT	MILD STEEL (GALV.)	SHELF
11.	1	PIECES	3/4" BSP M BACKING NUT TANK ACCESSORY	POLYPROPYLENE	SHELF
12.	5	PIECES	3/4" BSP F - 1/2" BSP M REDUCER	POLYPROPYLENE	SHELF
13.	7	PIECES	1/2" BSP F-F UNION	POLYPROPYLENE	SHELF
14.	6	PIECES	1/2" BSP M STRAIGHT BARBED HOSE FITTING	POLYPROPYLENE	SHELF
15.	15	PIECES	1/2" HOSE CLAMP OR EQUIVALENT	ALUMINIUM	SHELF
16.	6	M	1/2" HOSE	RUBBER	SHELF
17.	2	PIECES	3/4" BSP M END CAP	POLYPROPYLENE	SHELF
18.	1	PIECES	3/4" BSP M VACUUM BREAKER VALVE	POLYPROPYLENE	SHELF
19.	1	PIECES	3/4" BSP F-F 90 DEGREE ELBOW	POLYPROPYLENE	SHELF
20.	1	PIECES	M5 X 10 NUT & BOLT	SS316	SHELF
21.	1	PIECES	1/2" BSP M QUICK HOSE CONNECTING NOZZLE	POLYPROPYLENE	SHELF
22.	1	PIECES	3/4" SLUDGE CONVEYOR	POLYPROPYLENE	CUSTOM
23.	1	PIECES	BAFFLE CHAMBER INSERT	MILD ST. (EPOXY CTD)	CUSTOM
24.	2	PIECES	1/2" PERFORATED PVC RING	PVC	CUSTOM
25.	4	PIECES	9" GRAVITY FILTER ELEMENT	N/A	SHELF
26.	12	PIECES	HOSE ELEVATORS	POLYPROPYLENE	CUSTOM
27.	7	PIECES	BAFFLE CHAMBER RING INSERT (VARYING DIAM)	MILD ST. (EPOXY CTD)	CUSTOM
28.	3	PIECES	1/2" BARBED HOSE T-PIECE CONNECTOR	POLYPROPYLENE	SHELF
29.	2	PIECES	10MM MESH SCREEN AND FRAME	POLYPROPYLENE	CUSTOM
30.	TBD	PIECES	ATTACHED GROWTH MEDIA	POLYPROPYLENE	CUSTOM
31.	1	PIECES	NYLON NET	NYLON	SHELF
32.	5	PIECES	Ø572 X 40 X 5MM GASKETS	RUBBER	CUSTOM
33.	1	PIECES	1/2" BSP M-M UNION	POLYPROPYLENE	SHELF
34.	3	PIECES	1/2" BSP F DIAPHRAGM VALVE	PVC	SHELF

Figure A-1.4: Bill of materials for the proposed technical solution

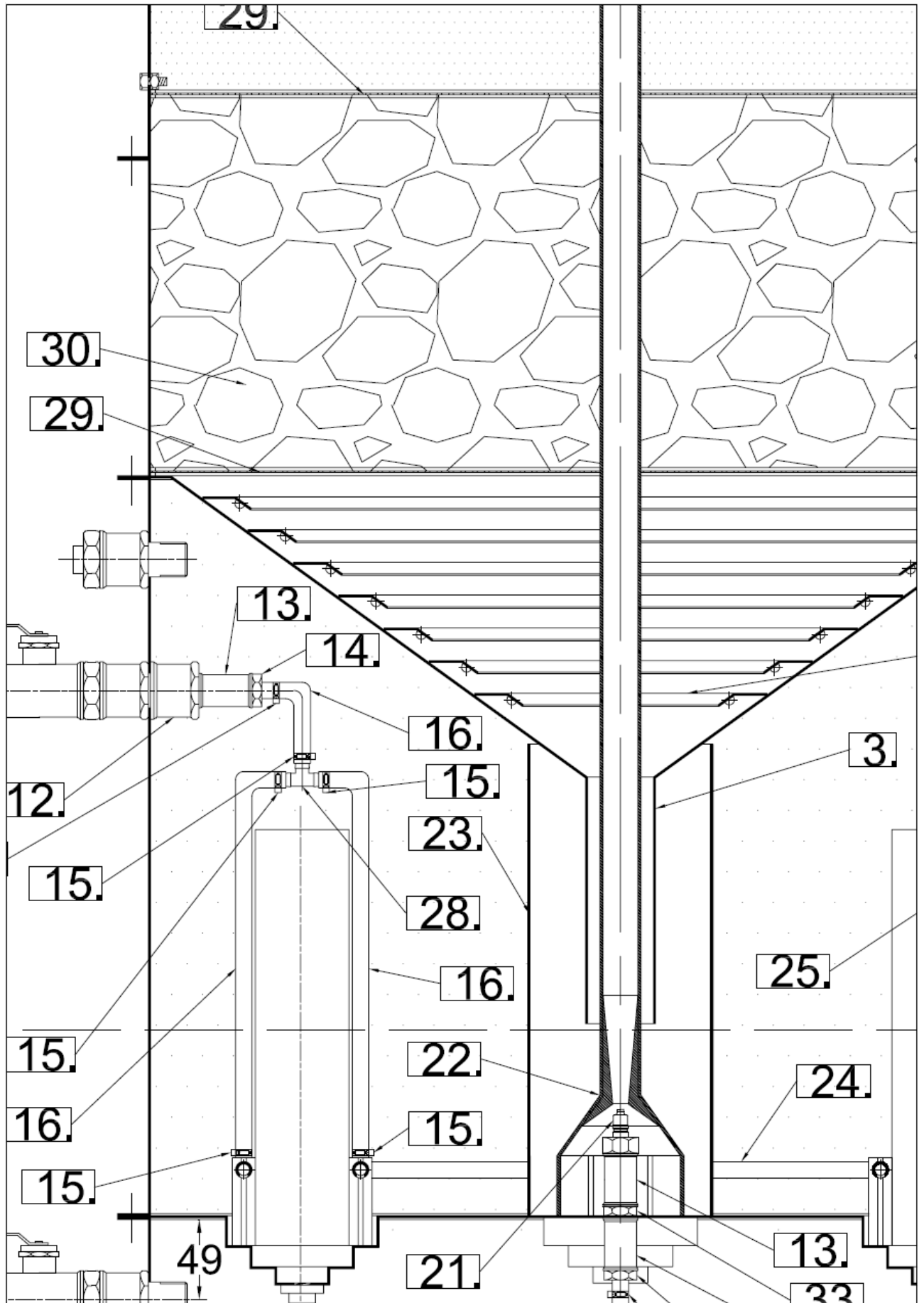


Figure A-2: A magnified view of the attached growth chamber, according to the present invention

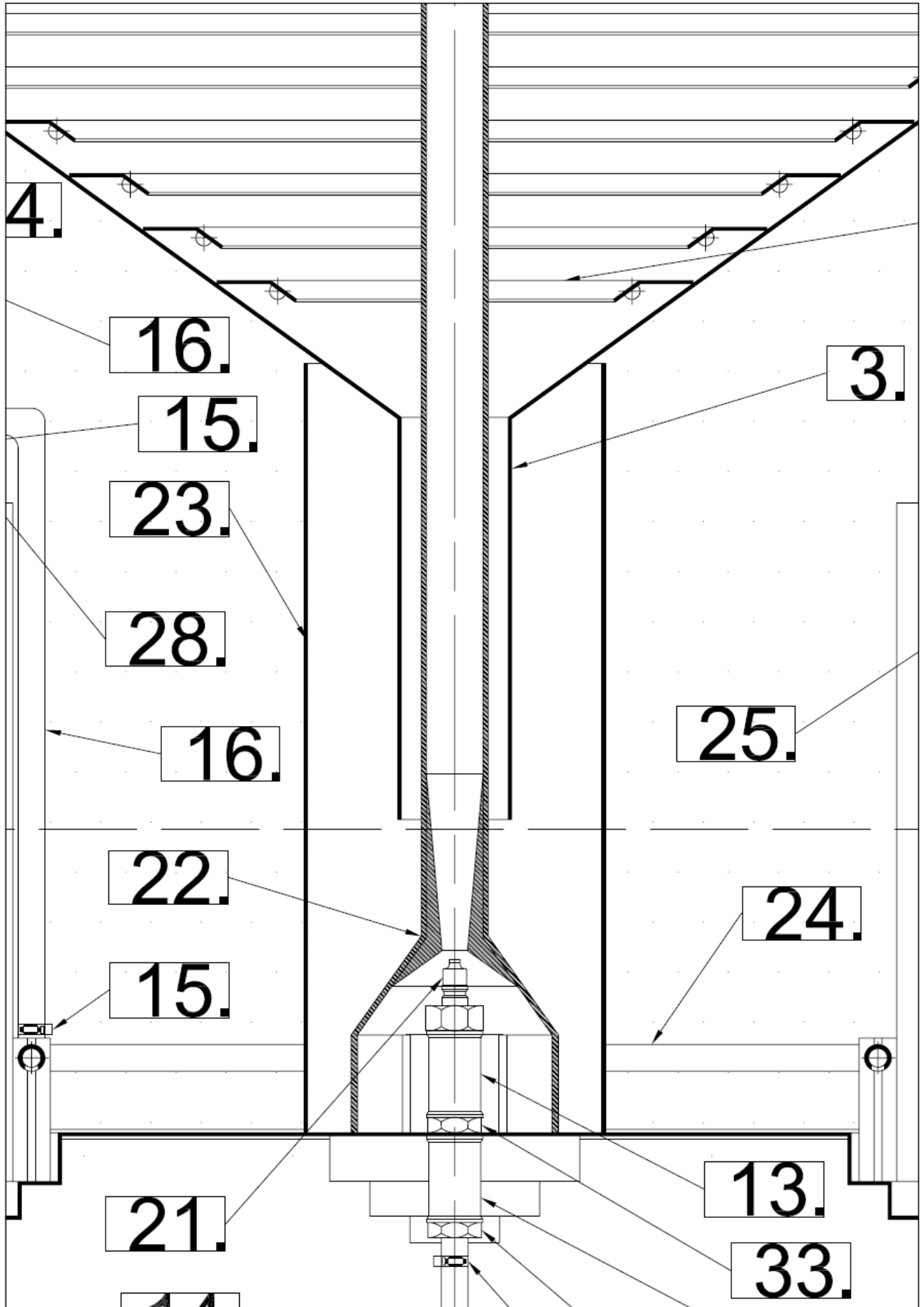


Figure A-3: A magnified view of the baffle chamber and the conical section, according to the present invention

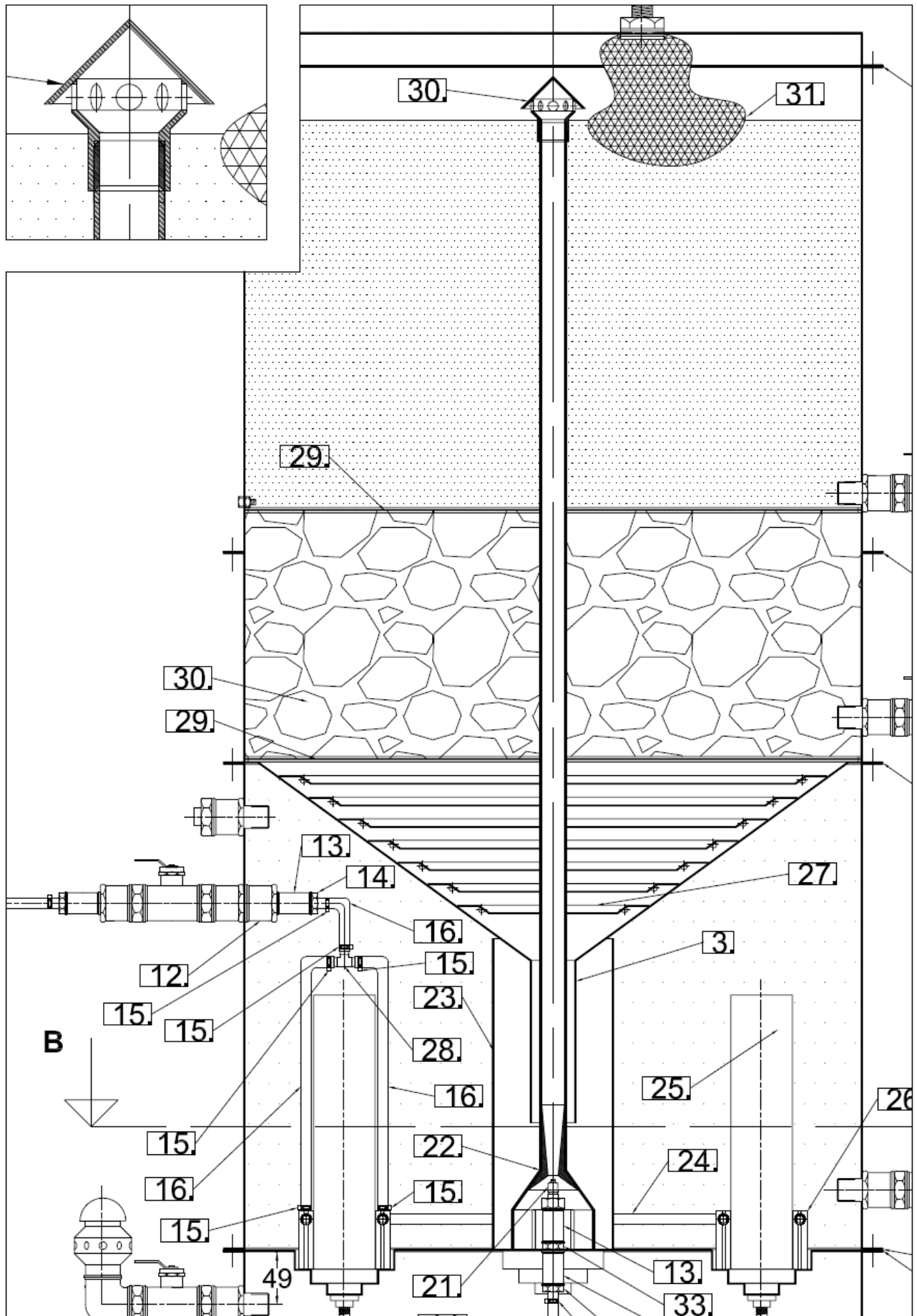


Figure A-4: A magnified view of the sludge conveyor (in the centre), according to the present invention

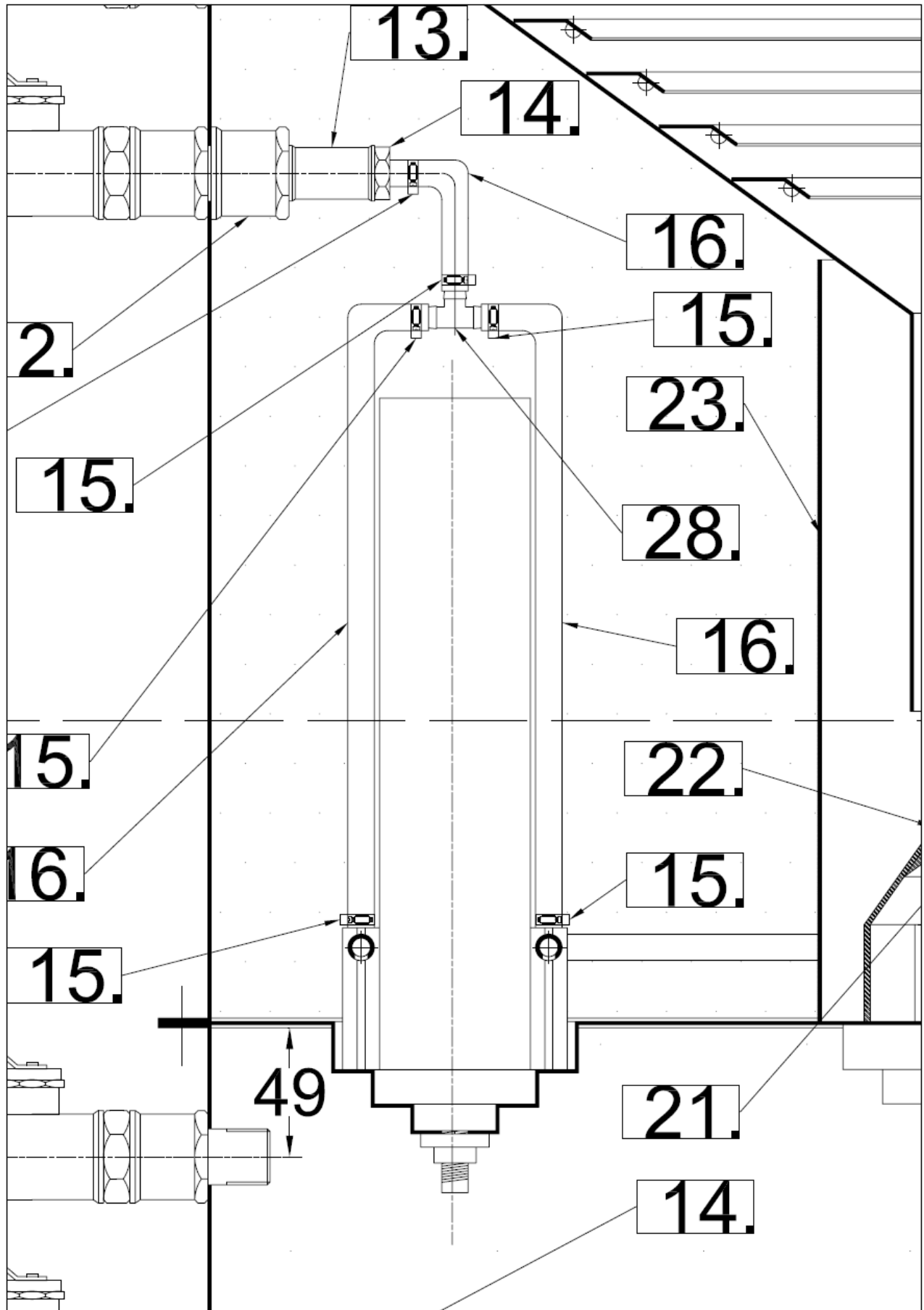


Figure A-5: A magnified view of filtration elements housed atop the baffle insert within the baffle chamber, according to the present invention

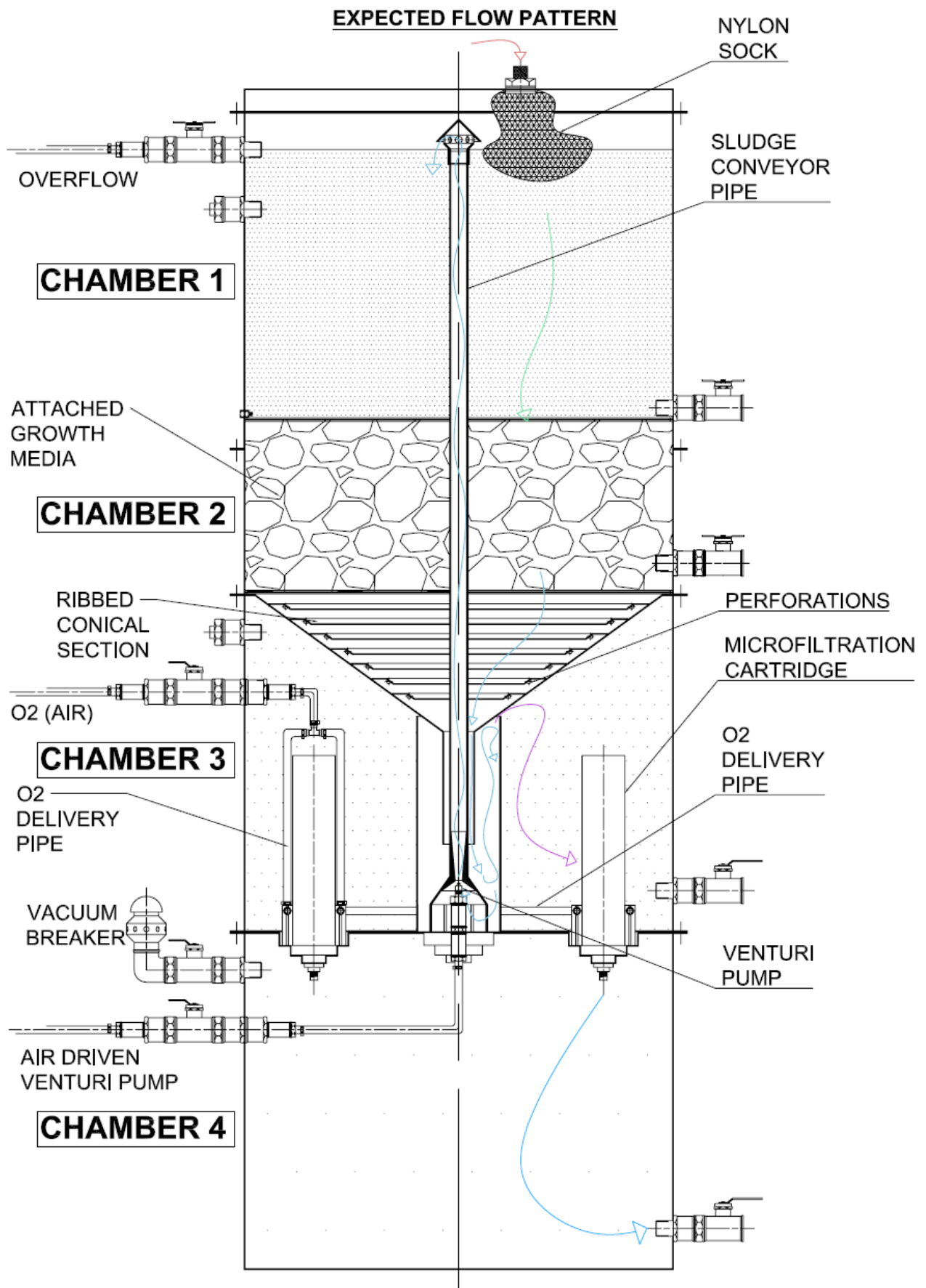


Figure A-6: An illustration of the expected hydraulic flow pattern, according to the present invention

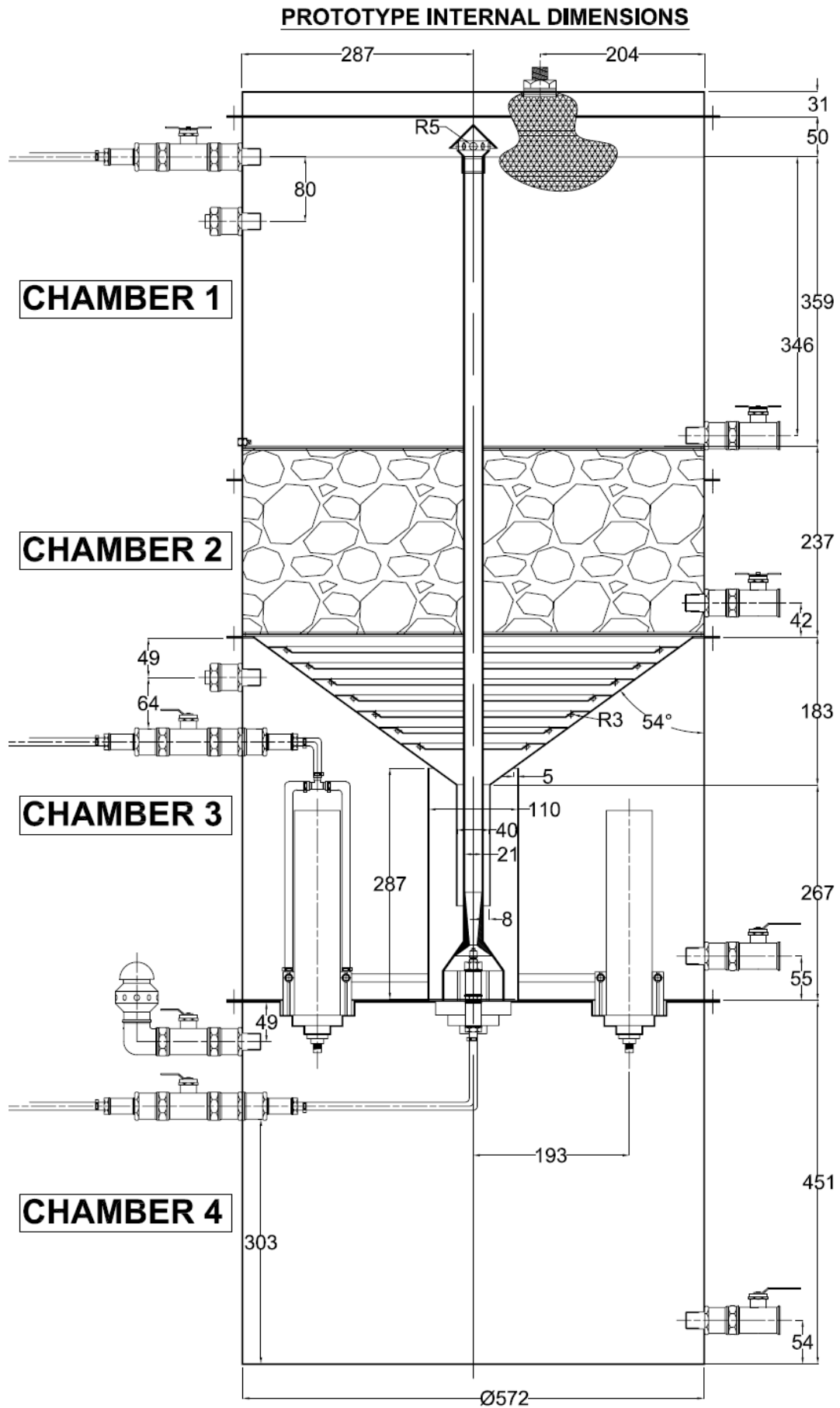


Figure A-7: Sectioned view (A-A) of the proposed technical solution, including the internal dimensions of the compact greywater recycler, according to the present invention

Annexure B – End user acceptability score sheets

Section 4.2.2 includes the acceptability score sheet generated for the AUQUALOOP 300. The score sheets for the three other commercial technologies considered for this project are provided below.

Technology Name: Aqua2UseGWTS 500

Dimension	Dim. Weight, w_x	Drawback weight	Drawbacks	Index Guide	Drawback Score
Technical	0.6	0.225	Unpleasant odour	1 = rarely 0 = regularly	1
		0.1	Deficient aesthetics of water	1 = rarely 0 = regularly	1
		0.225	Floor Space	1 if < 1 m ² 0 if > 1m ²	1
		0.225	Device mobility	1 = Portable 0 = Fixed	0
		0.225	Complexity	1 = simple ²⁸ 0 = complex ⁹	0
Economic	0.36	0.5	Monthly running costs (incl. replacement cost)	1 = less than 0.5% of monthly household income 0 = greater than 0.5% of monthly household income	0
		0.5	Purchase Price	1 if < 50% monthly salary 0 if > 50% monthly salary	0
Social	0.03	0.4	Behavioural requirements	1 = Little to no behavioral change needed 0 = Major behavioural change needed	1
		0.6	Children surveillance	1 = Little to no behavioral change needed 0 = Major behavioural change needed	1
Institutional	0.01	1	Availability of local technical support ²⁹	1 = Local technical support readily available 0 = Local technical support not available	0
					$\beta = 0.36$

²⁸ If treatment device contains more than 2 electro-mechanical components, it is regarded as being a complex design.

²⁹ i.e. Within South Africa

Technology Name: RECOVER

Dimension	Dim. Weight, w_x	Drawback weight	Drawbacks	Index Guide	Drawback Score
Technical	0.6	0.225	Unpleasant odour	1 = rarely 0 = regularly	1
		0.1	Deficient aesthetics of water	1 = rarely 0 = regularly	0
		0.225	Floor Space	1 if < 1 m ² 0 if > 1m ²	1
		0.225	Device mobility	1 = Portable 0 = Fixed	0
		0.225	Complexity	1 = simple ³⁰ 0 = complex ⁹	0
Economic	0.36	0.5	Monthly running costs (incl. replacement cost)	1 = less than 0.5% of monthly household income 0 = greater than 0.5% of monthly household income	1
		0.5	Purchase Price	1 if < 50% monthly salary 0 if > 50% monthly salary	0
Social	0.03	0.4	Behavioural requirements	1 = Little to no behavioral change needed 0 = Major behavioural change needed	1
		0.6	Children surveillance	1 = Little to no behavioral change needed 0 = Major behavioural change needed	1
Institutional	0.01	1	Availability of local technical support ³¹	1 = Local technical support readily available 0 = Local technical support not available	0
					$\beta = 0.48$

³⁰ If treatment device contains more than 2 electro-mechanical components, it is regarded as being a complex design.

³¹ i.e. Within South Africa

Technology Name: HYDRALOOP R

Dimension	Dim. Weight, w_x	Drawback weight	Drawbacks	Index Guide	Drawback Score
Technical	0.6	0.225	Unpleasant odour	1 = rarely 0 = regularly	1
		0.1	Deficient aesthetics of water	1 = rarely 0 = regularly	1
		0.225	Floor Space	1 if < 1 m ² 0 if > 1m ²	1
		0.225	Device mobility	1 = Portable 0 = Fixed	0
		0.225	Complexity	1 = simple ³² 0 = complex ⁹	0
Economic	0.36	0.5	Monthly running costs (incl. replacement cost)	1 = less than 0.5% of monthly household income 0 = greater than 0.5% of monthly household income	1
		0.5	Purchase Price	1 if < 50% monthly salary 0 if > 50% monthly salary	0
Social	0.03	0.4	Behavioural requirements	1 = Little to no behavioral change needed 0 = Major behavioural change needed	1
		0.6	Children surveillance	1 = Little to no behavioral change needed 0 = Major behavioural change needed	1
Institutional	0.01	1	Availability of local technical support ³³	1 = Local technical support readily available 0 = Local technical support not available	0
					$\beta = 0.54$

³² If treatment device contains more than 2 electro-mechanical components, it is regarded as being a complex design.

³³ i.e. Within South Africa

Annexure C – A detailed explanation of life-cycle costs used in this study

Table 26 of Section 4.2.3, note 20 refers. Maintenance costs refer to costs associated with the labour required to service the treatment device. Consumables cost refers to chemicals needed for the daily operation of the treatment device, such as chemical disinfectants. Replacement costs refer to components of the treatment device which will need to be replaced over the lifetime of the device. Each of the three cost components (maintenance, consumables and replacement) were calculated for each of the technologies as described in Table 36 (below). All costs reported below are those advertised to the public by the supplier, unless stated otherwise.

Table 36: Explanation of life-cycle costs for each technical solution

	AQUALOOP	AQUA2USE	RECOVER	HYDRALOOP	PROTOTYPE
Energy	1.4kWh/m ³	(79.3Watts x 24hours) / 0.5m ³ per day	(40kWh/365days) / 0.2m ³ per day	110kWh/(365 days x 0.44m ³ /day)	8.5Watts x 24 hours/0.232 m ³ per day
Maintenance	Cost of annual service over 12 months (i.e. R1250/12)	No local agent. Used the same maintenance cost as that of Aqualoop	No local agent. Used the same maintenance cost as that of Aqualoop	No local agent. Used the same maintenance cost as that of Aqualoop	None. Can be serviced by owner
Consumables	None	None	No supplier data. Dosage requirement of 8.9mg CL ₂ /l selected (March & Gual, 2007). This translates to 51ml of sodium hypochlorite (e.g. household bleach such as JIK, 3.5%) being needed per 200 litres. At R26/l for hypochlorite, this equates to R40 per month.	None	sodium hypochlorite (3.5%) costs approx R26/l. So, requiring 33ml per day for 30 days = 1 litre of hypochlorite per month, costs R26 per month.
Replacement	Cost of pump (R7000) replacement over 48 months + cost of membrane (R13000) replacement over 120 months.	Cost of blower air filters and UV lamp (100\$) over 18 months.	Cost of inline strainer (5\$) over 12 months.	Cost of UV lamp (10 Euro) over 12 months + water pump (50 Euro) over 48 months.	Replacement cost of air blower over 7x12 months and the filtration elements (R100 each) over 6 months.

Table 37: Calculation results for NPV - AQUALOOP 300

Year, t	Investing Cash Flows	Operating Cash Flows	Total Cash Flows	NPV _{t}
0	-65000.00	-1703.81	-66703.81	-1703.81
1		-1797.52	-1797.52	-3375.76
2		-1896.38	-1896.38	-5016.46
3		-2000.68	-2000.68	-6626.48
4		-2110.72	-2110.72	-8206.40
5		-2226.81	-2226.81	-9756.79
6		-2349.29	-2349.29	-11278.19
7		-2478.50	-2478.50	-12771.14
8		-2614.81	-2614.81	-14236.18
9		-2758.63	-2758.63	-15673.83
10		-2910.35	-2910.35	-17084.60
11		-3070.42	-3070.42	-18469.00
12		-3239.30	-3239.30	-19827.51
13		-3417.46	-3417.46	-21160.63
14		-3605.42	-3605.42	-22468.82
15	0.00	-3803.71	-3803.71	-23752.56
			Final NPV	-88,752.56

Table 38: Calculation results for NPV – Aqua2Use GWTS 500

Year, t	Investing Cash Flows	Operating Cash Flows	Total Cash Flows	NPV _{t}
0	-105300.00	4510.44	-100789.56	4510.44
1		4758.51	4758.51	8936.55
2		5020.23	5020.23	13279.92
3		5296.35	5296.35	17542.08
4		5587.64	5587.64	21724.55
5		5894.97	5894.97	25828.83
6		6219.19	6219.19	29856.38
7		6561.24	6561.24	33808.62
8		6922.11	6922.11	37686.98
9		7302.83	7302.83	41492.83
10		7704.48	7704.48	45227.52
11		8128.23	8128.23	48892.39
12		8575.28	8575.28	52488.74
13		9046.92	9046.92	56017.86
14		9544.50	9544.50	59480.99
15	0.00	10069.45	10069.45	62879.38
			Final NPV	-42 420.62

Table 39: Calculation results for NPV – RECOVER® Greywater Treatment System

Year, t	Investing Cash Flows	Operating Cash Flows	Total Cash Flows	NPV $_t$
0	-44135.00	-1353.10	-45488.10	-1353.10
1		-1427.52	-1427.52	-2680.89
2		-1506.03	-1506.03	-3983.87
3		-1588.86	-1588.86	-5262.48
4		-1676.25	-1676.25	-6517.19
5		-1768.44	-1768.44	-7748.44
6		-1865.71	-1865.71	-8956.67
7		-1968.32	-1968.32	-10142.31
8		-2076.58	-2076.58	-11305.79
9		-2190.79	-2190.79	-12447.51
10		-2311.28	-2311.28	-13567.89
11		-2438.40	-2438.40	-14667.32
12		-2572.52	-2572.52	-15746.20
13		-2714.00	-2714.00	-16804.90
14		-2863.27	-2863.27	-17843.82
15	0.00	-3020.75	-3020.75	-18863.30
			Final NPV	-62 998.30

Table 40: Calculation results for NPV – HYDRALOOP® Greywater Treatment System

Year, t	Investing Cash Flows	Operating Cash Flows	Total Cash Flows	NPV $_t$
0	-47920.00	5173.59	-42746.41	5173.59
1		5458.14	5458.14	10250.45
2		5758.33	5758.33	15232.40
3		6075.04	6075.04	20121.20
4		6409.17	6409.17	24918.60
5		6761.67	6761.67	29626.31
6		7133.56	7133.56	34246.01
7		7525.91	7525.91	38779.34
8		7939.84	7939.84	43227.91
9		8376.53	8376.53	47593.31
10		8837.24	8837.24	51877.10
11		9323.28	9323.28	56080.79
12		9836.06	9836.06	60205.90
13		10377.05	10377.05	64253.88
14		10947.78	10947.78	68226.18
15	0.00	11549.91	11549.91	72124.22
			Final NPV	24 204.22

Table 41: Calculation results for NPV of prototype design

Year, t	Investing Cash Flows	Operating Cash Flows	Total Cash Flows	NPV $_t$
0	-16055.00	838.67	-15216.33	838.67
1		884.79	884.79	1661.65
2		933.46	933.46	2469.25
3		984.80	984.80	3261.75
4		1038.96	1038.96	4039.43
5		1096.10	1096.10	4802.58
6		1156.39	1156.39	5551.45
7		1219.99	1219.99	6286.33
8		1287.09	1287.09	7007.47
9		1357.88	1357.88	7715.12
10		1432.56	1432.56	8409.54
11		1511.35	1511.35	9090.99
12		1594.48	1594.48	9759.69
13		1682.17	1682.17	10415.89
14		1774.69	1774.69	11059.82
15	0.00	1872.30	1872.30	11691.71
			Final NPV	-4 363.29

Annexure D – Component costs for the proposed technical solution

Bill of Materials - Prototype Design					Cost Estimate		
Item #	Qty	Unit	Description	Material	Source	Unit Cost	Total Cost
1	1	Pieces	Cylindrical section Chamber 4	Mild steel (Epoxy coated)	Custom	R1,200.00	R1,200.00
2	1	Pieces	Cylindrical section Chamber 3	Mild steel (Epoxy coated)	Custom	R1,200.00	R1,200.00
3	1	Pieces	Cylindrical section Chamber 2	Mild steel (Epoxy coated)	Custom	R1,200.00	R1,200.00
4	1	Pieces	Cylindrical section Chamber 1	Mild steel (Epoxy coated)	Custom	R1,200.00	R1,200.00
5	1	Pieces	Cylindrical cap	Mild steel (Epoxy coated)	Custom	R800.00	R800.00
6	10	Pieces	3/4" BSP M-F Adapter	SS316	Shelf	R25.00	R250.00
7	12	Pieces	3/4" BSP M-M Union	Polypropylene	Shelf	R20.00	R240.00
8	5	Pieces	3/4" BSP Compact Ball Valve	Polypropylene	Shelf	R50.00	R250.00
9	32	Pieces	M5 x 20 Bolt	Mild steel (Galv.)	Shelf	R2.50	R80.00
10	32	Pieces	M5 Nut	Mild steel (Galv.)	Shelf	R2.50	R80.00
11	1	Pieces	3/4" BSP M Backing Nut Tank Accessory	Polypropylene	Shelf	R50.00	R50.00
12	5	Pieces	3/4" BSP F - 1/2" BSP M Reducer	Polypropylene	Shelf	R25.00	R125.00
13	7	Pieces	1/2" BSP F-F Union	Polypropylene	Shelf	R20.00	R140.00
14	6	Pieces	1/2" BSP M Straight Barbed Hose Fitting	Polypropylene	Shelf	R25.00	R150.00
15	15	Pieces	1/2" Hose Clamp or Equivalent	Aluminium	Shelf	R5.00	R75.00
16	6	M	1/2" Hose	Rubber	Shelf	R20.00	R120.00
17	2	Pieces	3/4" BSP M End Cap	Polypropylene	Shelf	R20.00	R40.00
18	1	Pieces	3/4" BSP M Vacuum Breaker Valve	Polypropylene	Shelf	R150.00	R150.00
19	1	Pieces	3/4" BSP F-F 90 Degree Elbow	Polypropylene	Shelf	R20.00	R20.00
20	1	Pieces	M5 x 10 Nut & Bolt	SS316	Shelf	R5.00	R5.00
21	1	Pieces	1/2" BSP M Quick Hose Connecting Nozzle	Polypropylene	Shelf	R50.00	R50.00
22	1	Pieces	3/4" Sludge Conveyor	Polypropylene	Custom	R700.00	R700.00
23	1	Pieces	Baffle Chamber Insert	Mild steel (Epoxy coated)	Custom	R2,000.00	R2,000.00
24	2	Pieces	1/2" Perforated PVC Ring	PVC	Custom	R100.00	R200.00
25	4	Pieces	9" Gravity Filter Element	Various	Shelf	R300.00	R1,200.00
26	12	Pieces	Hose Elevator	Polypropylene	Custom	R20.00	R240.00
27	7	Pieces	Baffle Chamber Ring Insert (varying diam)	Mild steel (Epoxy coated)	Custom	R150.00	R1,050.00
28	3	Pieces	1/2" Barbed Hose T-Piece Connector	Polypropylene	Shelf	R50.00	R150.00
29	2	Pieces	10mm Mesh Screen and Frame	Polypropylene	Custom	R250.00	R500.00
30	TBD	Pieces	Attached Growth Media	Polypropylene	Custom	R500.00	R500.00
31	1	Pieces	Nylon Net	Nylon	Shelf	R20.00	R20.00
32	5	Pieces	572x20x5mm Rubber gasket	Rubber	Custom	R150.00	R750.00
33	1	Pieces	1/2" BSP M-M Union	Polypropylene	Shelf	R20.00	R20.00
34	3	Pieces	1/2" BSP F DIAPHRAGM VALVE	PVC	Shelf	R100.00	R300.00
NA	1	Pieces	8.5 W HIBLOW CD-8S Linear Air Pump	Various	Shelf	R1,000.00	R1,000.00
						Total Cost, Excl. VAT	R16,055.00

Annexure E – Blower specifications for the linear air pump required for the proposed technical solution

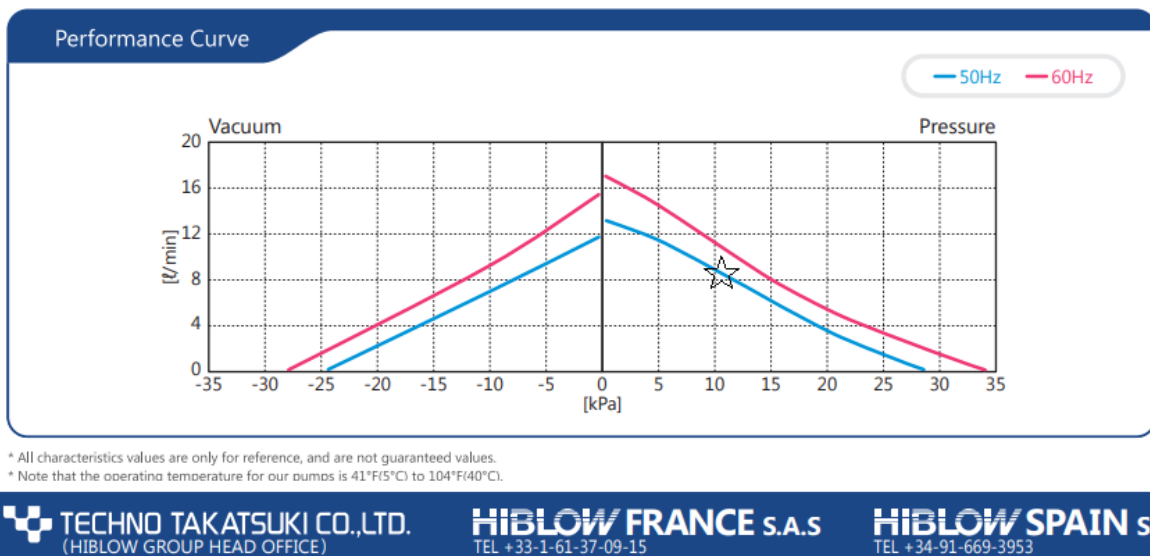
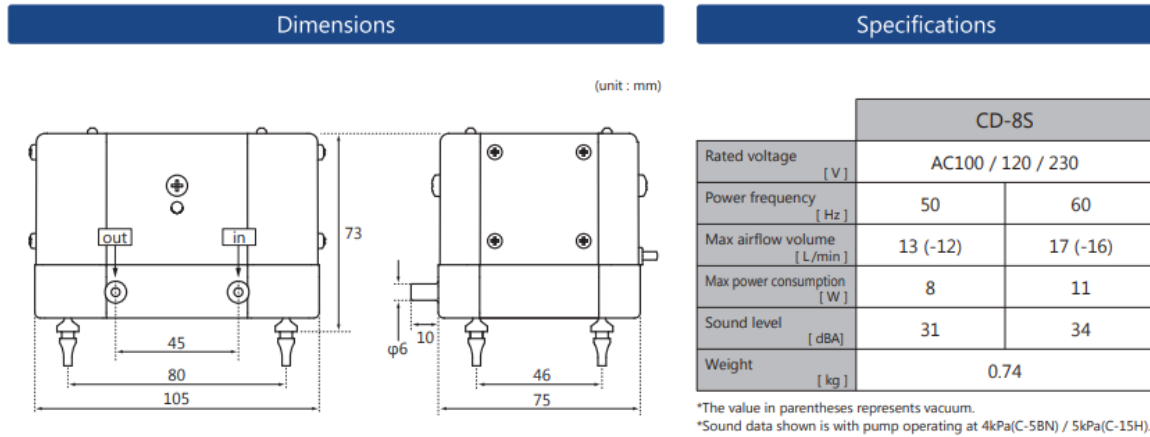


Figure E-1: Performance curves for the 8.5W HIBLOW CD 8S linear air pump, indicating the expected operating point (considering the water column above the air delivery pipes) (Maskam Water, 2018).