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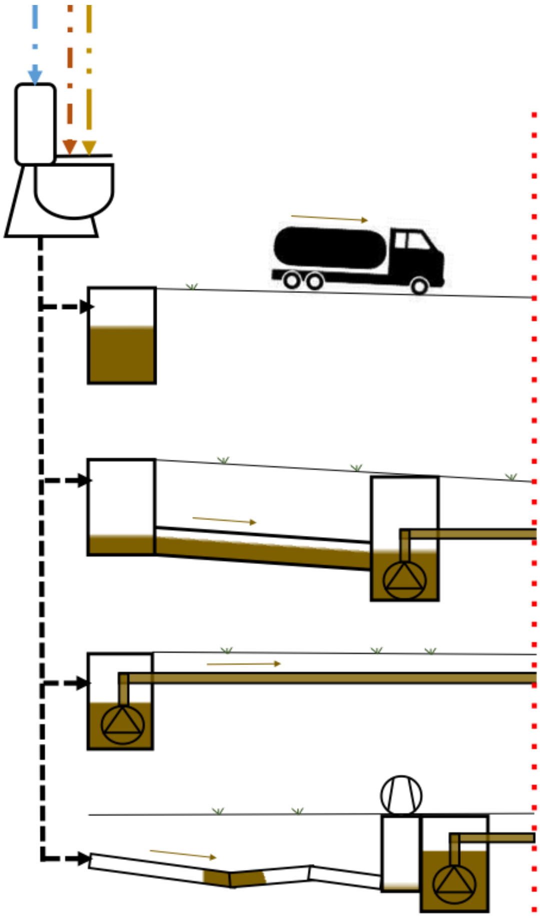

Sustainability of Sewer Systems for Source Separated Blackwater

Low pressure, vacuum and gravity systems for case Munga

Master's thesis in Nordic Five Tech Master Programme Urban Water
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Cover: Flow chart visualisation of system alternatives

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Abstract

Source separation of sewage into different fractions has potential to mitigate arising problems from climate change, resource scarcity and urbanisation through control over wastewater volume produced and simplified treatment and nutrient reuse. Merely around 30% of the daily domestic wastewater discharge is dirty toilet waste (blackwater), containing 3/4 of the phosphorus discharge. However a lack of knowledge on reliability and sustainability of blackwater sewer systems exists and the rate of implementation is limited. This paper analyses and compares sustainability of three blackwater sewer alternatives in a desk study for a case area described as rural—urban transition zone to assist considerations for similar cases. Analysis by selecting and scoring indicators inside predefined framework consisting of five aspects: economic, environmental, health and hygiene, socio-cultural, and technical function criteria. Results aggregated with help of multi-criteria analysis suggest following ranking in the order of sustainability: vacuum sewer, gravity sewer, low-pressure sewer, and tank truck collection. Low dilution of wastewater from vacuum system was recognised as dominant variable in all but socio-cultural aspect where technology-user nexus presents a challenge for sustainability. Results provide an established overview on considerations for similar developments, whilst the theory section functions as objective reference and introduction to specified technologies.

Keywords: decentralisation, wastewater, sustainability, sewer systems, source separation, blackwater, low-pressure, vacuum, gravity sewer

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Ville Tanskanen, Gothenburg, April 2018

Contents

Wastewater
Water influenced by human activities resulting in degenerated quality, origins in industrial, commercial, agricultural domestic functions or surface runoff

Stormwater
Surface runoff, which can be conveyed combined with sewage or in a separate system

Sewage (also domestic wastewater or municipal wastewater)
Wastewater from housing or similar functions, produced by a community of people

Blackwater
Toilet fraction of sewage containing human waste (urine and feaces), flushing water and toilet paper

Greywater Washing water fraction of sewage originating from sinks, showers, dishwashers, laundry and showers

TSS Total Suspended Solids

ULFT Ultra Low Flush Toilet

DFT Dual Flush Toilet

NASS New Alternative Sanitation Systems

SRT Sustainability Reporting Tools

MCA Multi Criteria Analysis

LCA Life Cycle Analysis

MDG Millenium Development Goal

SDG Sustainable Development Goal

WC Conventional Flush Toilet (Water Closet)

mwc meters water column, derivative unit of pressure

1
Introduction

Decentralisation and centralisation of wastewater treatment are commonly emerging, opposing and persistent topics in wastewater treatment dialogue. As centralised wastewater treatment has been the proven method to control substance and pollutant levels in effluent, the paradigm is slowly shifting around to resource reuse and meta-level focus on wastewater as a part of metabolism of a human population. The idea of wastewater as a metabolic product allows a broader view and leads to the concept of a circular economy where the metabolic product is circulated back into substrate and energy for metabolism. This concept can be supported both on decentralised and centralised level and is very much dependent on practical implications of the existing wastewater management system. Diving deeper into the idea of wastewater reuse as resource there is another persistent topic that surfaces: Source separation of wastewater. The idea of source separation of wastewater in a nutshell is to separate human waste fractions from pathogenically uncontaminated washing water fraction. The benefits of doing this are further on discussed in detail but consist mostly of benefits of a more concentrated wastewater flow that is easily applicable for nutrient reuse. Generally the reasons for renewed and strengthened focus on alternative meta level concepts of wastewater management, and on source separation, are connected to emerging and pressing world wide issues such as climate change, resource scarcity and urbanisation. These reasons demand a re-evaluation of western culture of water use and an increased attention on sustainability of wastewater management and pave the foundation for this thesis work.

Among many Grafton et al. (2015) and Davis et al. (2016) have recognised trends and challenges for sustainability of wastewater management. These include analysis of flows of energy, water and nutrients through the system; simul-analysing effects on water-energy-food-climate nexus and development of tools and performance metrics for measuring sustainability of systems. "Many of the hottest emerging topics in the area of sustainability relate to translating abstract or complex knowledge into components that will help effect real-world change" (Davis et al., 2016). Sharma et al. (2010), Böhm et al. (2011), Arnold et al. (2013), Larsen et al. (2013), Sapkota et al. (2014), Naik and Stenstrom (2016), and Siegrist (2017) among others have highlighted the possibilities of decentralised and hybrid wastewater management systems as a way for countering the various challenges of sustainability. Among the recognised challenges by the authors are lack of knowledge on reliability, sustainability and resilience of these systems, due to lack of experience from implemented systems. As one possible way of organising decentralised wastewater management, source separation and in specific the separtion of the toilet fraction (blackwater), has been recognised as a viable method to improve the treatability of wastewater and the quality of the end product by many, including Jönsson, Nordberg, and Vinnerås (2013), Larsen et al. (2013), Kjerstadius et al. (2015), Londong, Wätzel, and Giese (n.d.), McConville et al. (2017), and Kärrman et al. (2017).

This master's thesis is a desk study on sustainability of source separating blackwater sewer systems. Studied sewer systems are used for conveying sewage originating from household toilets (referred to as blackwater further on). Paying detailed attention on blackwater is reasoned by its higher concentration of solids, nutrients, and contaminants when compared to other household wastewater from washing and showers (referred to as greywater further on), and thus more challenging consistency for the sewer system. The method utilised in this sustainability study is indicator based multi-criteria analysis according to sustainability assessment framework by Malmqvist et al. (2006). The method is established by recognising relevant indicators applicable for assessment of sewers through literature research and gathering data for the recognised indicators from pilot-projects and literature sources. The technologies studied are conventional gravity system, low-pressure system and vacuum system for blackwater transport. The following research question is considered essential: What are the primary variables that contribute to sustainability of a specific technology for a given case?

1.1 Aim

The aim of the thesis is to:

- Develop and define a method and selection of indicators for analyzing sustainability of different blackwater sewer systems in peri-urban context based on previous research and ongoing pilot projects

- Analyse sustainability of specified sewer alternatives by conducting a case study on pilot project area Munga in Västerås, Sweden

- Determine factors essentially affecting the overall sustainability of a given technology in similar cases

1.2 Objectives

- Define sewer system alternatives
- Define criteria and indicators to be used
- Weight the defined criteria and indicators
- Score the indicators and alternatives for case-study
- Compare sustainability of alternatives for case-study
- Discuss results and key variables influencing end-result of case-study

- Conclude with key variables to be considered for overall sustainability

1.3 Delimitation

The study focuses on three different sewer technologies for blackwater as mentioned forehand. Accompanying greywater systems are omitted from this study as the greywater system is considered independent of the chosen blackwater sewer system. The wastewater systems covered in this study are limited to systems applicable for peri-urban areas in Sweden as the case study area is defined as such area. This limitation is done to avoid vastly different environmental conditions, and drivers for system implementation that apply for other types of areas, such as single housing units or urban areas implementing source separation.

Lifetime for each sewer system is set to 50 years as an acceptable lifetime of sewer system components without major rehabilitation. This is a major simplification causing limitation as differing solution and material selections would in reality inflict a varying lifetime, that would further-on affect economic sustainability of specific system in substantial way. In addition, all systems are considered as new construction not taking into account any presently installed systems. However this assumption is in reality invalid as closed tank collection presents accurately the current system in the study area. Another major limitation of the study comes from areal limitation as transport distance from treatment to reuse location in agriculture which sets the boundary for the quantitative parts of the study. From reuse perspective only qualitative properties caused directly by studied systems are considered. The limitations and their effects are discussed further in chapter 4. Conceptual model of flow fractions, and systems for source separated blackwater, considered in this study are shown in figure 1.1.

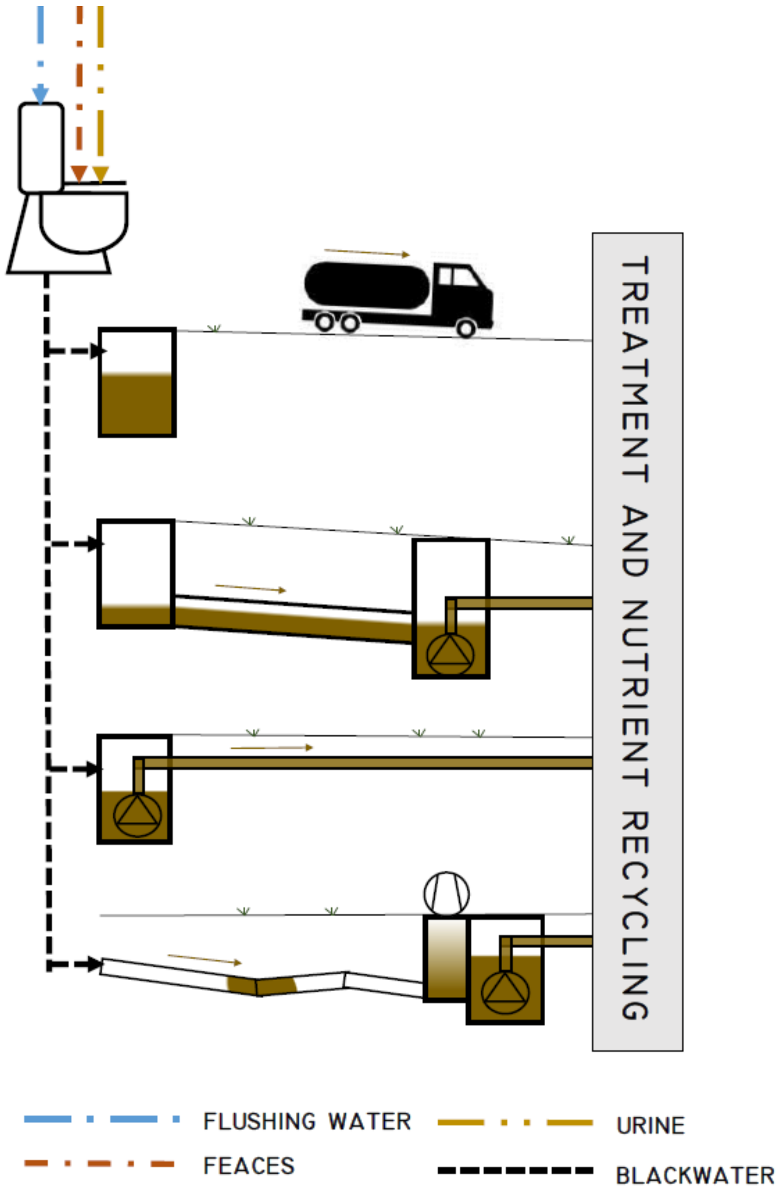

Figure 1.1: Conceptual model

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Theory

The theory chapter presents the theoretical background and details and assumptions made on each of the studied wastewater systems, and on sustainability analysis. The first part of the theory chapter connects the thesis into wider context in the Swedish effort of advancing circular economy for nutrients. The second part presents different wastewater systems. The third section covers the different frameworks and criteria as a background for analysing sustainability of wastewater management projects.

The wastewater collection system typically comprises of drainage systems for both wastewater and stormwater and these can be combined or separate within the system. Requirements for a functional urban water system by include: providing clean water for all required uses, removing wastewater and promoting hygiene, and removing stormwater to prevent flooding. The dimensions of the wastewater system thus need to be adequate for transporting all water delivered to the buildings, and the stormwater system for a design rainfall event (Butler, 2010; Hellström, Jeppsson, and Kärrman, 2000).

On a general level wastewater collection systems are coarsely defined as conventional or un-conventional, dependent on if the system is powered by gravity or needs a steady input of auxiliary energy to function (Miszta-Kruk, 2016). Another distinction can be made between traditional or alternative sanitation system, dependant on if all wastewater is collected combined or some fractions (e.g. toilet wastewater and washing wastewater) are collected separately within their own parallel sewer systems.

The categorization of sewer systems adapted from Miszta-Kruk (2016) is shown in figure 2.1. Gravity sewer systems are considered conventional systems and divided into two sub-categories either designed to collect storm water combined in one system or separate in a parallel system from the industrial and domestic wastewater. Pressure and vacuum sewer systems are considered as unconventional disposal systems. In the pressure sewer system exists two categories in which the systems are divided by the prevailing pressure: Low pressure achieved via centrifugal pumps, whilst high pressure is achieved with positive displacement pumps. Vacuum sewer systems can be divided into pure vacuum systems and vacuum systems with siphon and further categorized according to the location of the vacuum interface (i.e. toilet or collection chamber).

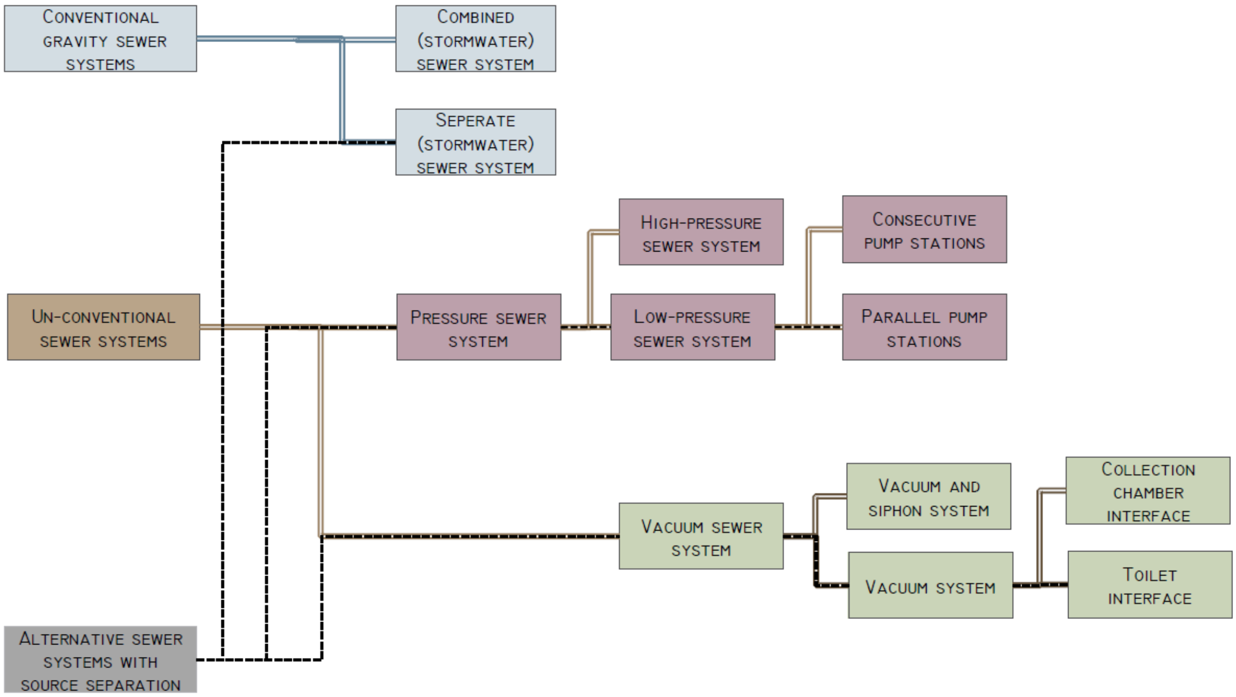

Figure 2.1: Categorization of wastewater sewer systems

2.1 Background

The background of the thesis lies in Vinnova-project MACRO (Mat I Cirkulära Robusta System), which concentrates in developing recycling of nutrient rich organic household waste to agriculture. The MACRO-project supports pilot studies and selection of technology for food waste and wastewater streams in H+ –housing area in Helsingborg and for separating black and grey wastewater in the peri-urban area of Munga in Västerås municipality. As a part of this project there is a need for sustainability analysis of different sewer solutions, with emphasis on technical evaluation. RISE, Technical Research Institutes of Sweden, has initiated the thesis project and it is conducted in close cooperation with Mälarenergi and NSVA to gain practical information of the ongoing pilot projects.

Munga source separation project with low pressure sewer system in Västerås was initiated by the local water utility Mälarenergi in cooperation with Urban Water Management AB to provide a sustainable wastewater solution for a peri-urban area with complex or varying geographical or topographical surface structure. The housing in the area consists of single-family houses used for permanent accommodation as well as houses for seasonal recreational use. From the total amount of 279 properties in the area approximately 47% are used for permanent housing and 53% for recreational use. The wastewater system development has advanced swiftly due to the wastewater utility's pro-active approach and was at moment of writing in construction stage. The chosen sewer system for blackwater is a low pressure sewer system with household specific pump stations complying with system alternative 1 presented in section 3.1.3. The chosen contractor for system construction is Skandinavisk Kommunalteknik AB (SKT). According to the contractor additional flushing posts are added network to guarantee a quick relief in case problems with stagnation and blockages occur. Majority of housing units rely on three chamber septic tank treatment systems (installed on 250 properties). The latest regulation for wastewater treatment systems in the area, valid since 2007, has been a requirement for closed tank system (installed on 29 properties). Free construction consulting is given to properties with newly renovated system but no compensation is paid for tank residual value. (Wallsten, 2017)

2.2 Wastewater systems and sustainability

Wastewater in specific contains a mixture of inorganic and organic substances in varying forms, ranging from coarse grit to fine suspended solids and from colloidal to soluble matter. In general wastewater is 99.9 % water with merely a fraction of substances problematic to water systems and potentially valuable as resources. The concentration and volume of domestic wastewater varies with time and location but tends to follow a diurnal pattern. Random point sampling and analysis techniques are thus subject to error and caution is advised when using standard or typical values for a specific community without control. Specific pollutant sources for domestic wastewater include human excreta, toilet waste (toilet paper, condoms, sanitary towels, tampons, disposable nappies, toilet tissue paper, paper towels, miscellaneous paper and miscellaneous fat), food, and laundry. (Butler, 2010, p. 61-74)

For wastewater management and systems Butler and Parkinson (1997) suggests three fundamental strategies: To reduce reliance on water as transport medium, to avoid mixing of industrial waste with domestic wastewater and to avoid mixing stormwater with wastewater, in order to reach sustainability. The first strategy, closely linked to the topic of source separation, consists of reducing water utilised for flush the toilet. Using water as transport medium causes multiple problems such as excessive water consumption, pollution of clean water, dilution of waste and requirement for costly end-of-pipe treatment. By reducing water consumption, introducing low flush toilets or vacuum systems the problem can be tackled. Potential drawback, from reducing the amount of carriage water, is however increased possibility of sedimentation and scaling in sewers. (Butler, 2010, p.593-615) The second and third mentioned strategies of separating industrial wastewater and stormwater from domestic wastewater support nutrient recycling as it separates the flow of many harmful contaminants and on the other hand eliminates an enormous volumetric flow of nutrient poor wastewater (stormwater).

Life-cycle of sewers has been studied by Akhtar et al. (2015), Vahidi et al. (2016), and Petit-Boix et al. (2016). The components of sewer life-cycle according to Akhtar et al. (2015) is presented in figure 2.2. In their study sewer life-cycle was divided into three parts: Manufacture, Construction and Operation & maintenance. The study however concentrated purely on economic and environmental impacts of sewer pipes neglecting the social considerations. Vahidi et al. (2016) however found that installation and material transportation only contribute a small effect of total impact from pipe material. For sewer systems with pumping the usage phase was found comparable to the manufacturing phase. The environmental impact of construction of sewers was estimated to be minimal. Vahidi et al. (2016) instead highlighted that life cycle environmental performance is only one of the factors that need to be considered when designing a sewer system. Other factors, such as seasonal temperature changes, corrosion, safety requirements, cost, trench conditions (geological conditions), and groundwater/soil chemistry were recognised as highly relevant. A major environmental benefit of re-using excavated material in respect to replacing with newly extracted materials was found by Petit-Boix et al. (2016). Global Warming Potential (GWP) of construction phase in kg CO^2 equivalents without reuse was found to increase by 37%.

There is an enormous need for renewing the current wastewater systems, as urban water systems around the globe are facing an imbalance between improvement need and actual implementation. This need consists of infrastructure rehabilitation, upgraded wastewater treatment, and the integration of water management with ecological requirements. (Malmqvist et al., 2006, p.1-6) According to Malm et al. (2013) the total length of the Swedish wastewater network amounted to 100,900 km in 2013 of which 60,200 km were separated sewer pipes. The emphasis on rehabilitation debt of current systems and the shear volume of the task presents another rational cause for replacement with alternative sewer systems. As decentralised source separation system can potentially provide shorter transport distances and cut down the length of network in need of rehabilitation.

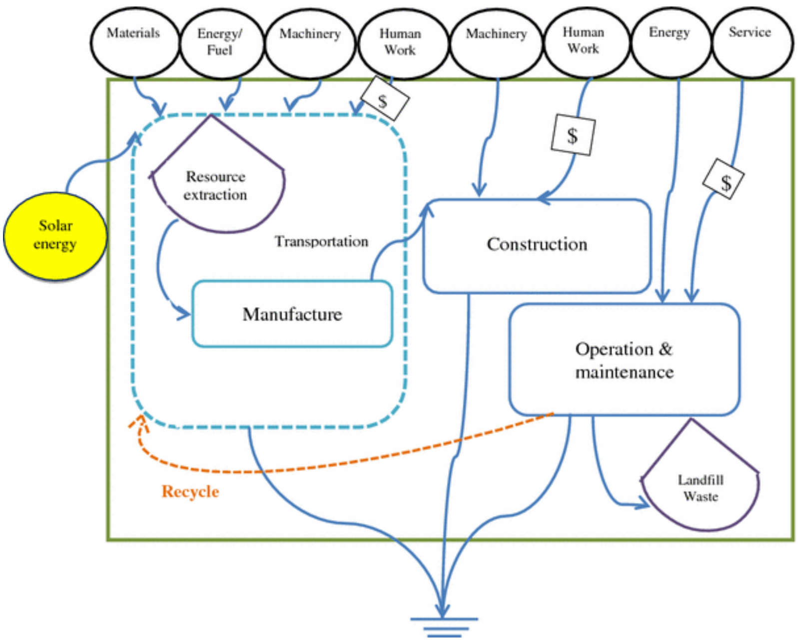

Figure 2.2: Life-cycle of sewers according to Akhtar et al. (2015)

Böhm et al. (2011), Larsen et al. (2013), Naik and Stenstrom (2016), and Arnold et al. (2013) have found benefits in decentralisation of wastewater treatment. Böhm et al. (2011) recommends a semi-centralised approach treatment of wastewater as better suited for fast growing urban areas than conventional centralised wastewater systems. According to Larsen et al. (2013, p. 471-472) there's a possibility for urban areas to improve ecosystem services of the surrounding watershed. Source separation and decentralisation can steer the attention to a local level of solving sustainability challenges promoting individual involvement in sustainability and climate change discourse. Feasibility analysis methodology of decentralised solutions by Naik and Stenstrom (2016) found that in the case study decentralised system was more economical and energy efficient than a centralised one. The main under laying reason being the pump energy consumption in the studied decentralised system which amounted to 50% of the aeration energy consumption for treatment compared to centralised system. Arnold et al. (2013) found that increased area demand, limited capacity, larger elevation variability, and lower discount rates favoured decentralised wastewater treatment and reclamation for irrigation purposes. They emphasise to note that the viability of wastewater reclamation is directly linked to the end-use of treated wastewater, affecting treatment requirement, and complexity of treatment process.

Reliability and failure of sewer networks for combined wastewater have been previously studied by Miszta-Kruk (2016) and Kowalski and Miszta-Kruk (2013). Miszta-Kruk (2016) studied the reliability of pressure, vacuum and gravity sewer systems based on data of 7 different large scale installations for a three to five year time period. Kowalski and Miszta-Kruk (2013) studied the failure intensity of wastewater networks in selected cities. Due to lack of data on dedicated blackwater systems, the data from combined wastewater systems is used for assessment of operational reliability and maintenance need in this study. Scaling in vacuum sewer systems for source separated blackwater has been studied by Rohde (2016). Findings imply that the factors influencing scaling in order of descending magnitude are: prior scaling, and leakages, flow velocity, and surface roughness, ambient temperature, and rinse water hardness. Sievers et al. (2016) has likewise studied vacuum system on a case study on Flintenbreite, Lübeck (Germany) and characterised source separated blackwater and greywater from the area.

Theoretical basis for a vacuum system is considered in detail as it is by far the most uncommon of studied technologies. Vacuum conveyance works through constant lower than atmospheric pressure (gauge pressure) in the collection network produced with a vacuum pump. Vacuum sewer systems work within a pressure range of $1 \cdot 10^5 Pa$ (1 bar) to $3 \cdot 10^3 Pa$ (0,03 bar), classified as low vacuum. Pressure range limits applicability of vacuum sewer as maximum lift or geodetic head is with common systems between 4 to 6 mwc. (Water Environment Federation, 2008; Islam, 2017) For simplified system diagram see section 3.1.4 and figure 3.5

For vacuum transport correct construction and hydraulic consideration are extremely important to guarantee a reliable system, Mäkinen (2016) specifies a saw tooth profile necessary to guarantee the proper transport function. In detail a minimum slope of 0.2% similar to gravity sewers, but always uphill is recommended by Water Environment Federation (2008). Typical failures in vacuum systems include blockages due to calcium-carbonate encrustations and foreign objects, observed in cruise boat context according to practical experiences by Heikkonen et al. (2016). Suggested remedies are frequently repeated acid dilution and manual mechanical cleaning procedure. Udert, Larsen, and Gujer (2003) suggests that dilution of urine with flushing water up to a factor of 1:18 can efficiently reduce precipitation potential and therefore prevent blockages in pipelines. This method is however often counterproductive to actual goal of source separation so its use should be carefully considered. In vacuum sewer systems with vacuum interface valves at collecting sumps, the interface accounted for 80% of system failures and of these failures 92% were observed to relate directly to operation of valve itself or its controller (Miszta-Kruk, 2016).

According to Remy and Jekel (2011) energy demand for vacuum collection of toilet wastewater is 15 $kWh/(pe * a)$ added with transfer energy use. Use of low-flush vacuum toilets in with vacuum collection reduces energy needed for flushing with drinking water by 3.5 $kWh/(pe * a)$. However Remy (2010) suggests that a wide range of energy demands has been observed for vacuum systems in pilot studies, energy demands ranging from 3 to 51 $kWh/(pe * a)$. Available vacuum sewer system manufacturers at moment of writing include: Evac, Jets, Bilfinger-Berger (Airvac and Roevac) and Iseki (Redivac).

2.3 Source separation and sewage fractions

The aim of source separation is to separate the different fractions of sewage at origin. This may be achieved through various technical solutions inside the housing units such as urine diversion, separating the toilet fraction with separate piping, or utilising dry toilets. The different fractions of sewage that can be separated are often described with names implying a characteristic colour of the fraction. The following definitions are given by Larsen et al. (2013, p. 471-472).

Yellowwater consists the urine excreted and the amount is roughly 1,270 $grams \cdot person^{-1} \cdot day^{-1}$ with water content of 95%. The remaining 5% consists of dissolved salts thus making it a saline solution. Urine contains most of the nitrogen excreted by humans.
Brownwater is the toilet waste excluding the yellowwater fraction. The amount humans excrete is roughly 200 $grams \cdot person^{-1} \cdot day^{-1}$ with a water content of 77%. Amount of disposed toilet paper is also considerable and it forms 11% of the TSS load.
Blackwater is a combined waste flow of yellowwater and brownwater that can also be described as the toilet fraction. The proportion of blackwater flow is 27 % of average daily domestic wastewater discharge of 148 $L \cdot person^{-1} \cdot day^{-1}$ in 11 countries observed, amounting to 40 $L \cdot person^{-1} \cdot day^{-1}$. According to Tidåker et al. (2006) 74% of wastewater phosphorus originating from Swedish households is found in blackwater.
Greywater is the remaining fraction of household wastewater and is fecally uncontaminated and thus contains minor amount of the total nutrients and suspended

solids making it often easily and cost efficiently treatable at close proximity of production.

Based on research by Butler, Friedler, and Gatt (1995), Larsen et al. (2013) defines the diurnal flow pattern for BW to follow general wastewater flow pattern with a peak discharge of 0.06 $L \cdot person^{-1} \cdot min^{-1}$ happening at 08:00. However the weekly variation for blackwater is described low when compared with overall variation of wastewater flows. The appliance wastewater use is presented in table 2.1. This table shows the data on flushing toilets as known as conventional flushing toilet (WC), Low flush toilets (LFT), Ultra low flush toilet (ULFT) and Vacuum toilet (VT).

Table 2.1: Wastewater production by appliances

Data source	Appliance	Average volume (l/use)
Butler and Parkinson (1997)	Conventional Flush Toilet (WC)	8.8
	Bath	74
	Shower	36
	Wash basin	3.7
	Kitchen sink	6.5
	Washing machine	116
Butler and Parkinson (1997)	Dual Flush Toilet (DFT)	5.0
Butler and Parkinson (1997)	Ultra Low Flush Toilet (ULFT)	1.5
Oldenburg et al. (2008)	Vacuum Toilet (VT)	0.7 - 1.2

Applied flush frequencies according to Eveborn et al. (2007), and flush volumes for toilet types considered in the study are specified in table 2.2. Blackwater properties used in this study according to Hertel et al. (2015), Tidåker et al. (2006), and Rohde (2016) are specified in table 2.3.

Table 2.2: Wastewater flush volumes and frequencies

Flush type	Flush amount [l]	Frequency [1/d]
DFT large flush	6	3
DFT small flush	4	5.5
VT large flush	1	3
VT small flush	1	5.5

Table 2.3: Blackwater properties

Property	Data source	Value [kg/ton]
Phosphorus concentration	Tidåker et al. (2006)	0.150
	Hertel et al. (2015)	0.162
	Rohde (2016)	0.160
Average		0.157
Dry matter concentration	Tidåker et al. (2006)	8.0
	Hertel et al. (2015)	6.0
	Rohde (2016)	8.3
Average		7.4

2.4 Sustainability analysis

Dissecting the terminology of sustainability and analysis is thought important as this clarifies an otherwise vague concept, and supports transparency of chosen method. Sustainability is commonly defined to comprise of three parts: environmental, socio-cultural and economical sustainability. History of definition of sustainability starts from the first recognised written version in the Brundtland-report (Our common future), as development that full-fills the needs and aspirations of the present generation, without compromising the possibility of future generations to full-fill theirs (Brundtland and Khalid, 1987). The definition was further refined to include aspects and criteria of environmental, economic and social sustainability by Stedman and Hill (1992). They stressed the importance of the ecological system as the basic life support system for all other systems, and highlighted economic sustainability, being dependent on if ecological principles and boundaries are followed. Social sustainability was also brought forward as a criteria, to ensure equitable distribution of benefits, and give a possibility of participation in decision processes when personally affected in a negative way by the proposed development.

More in depth definition of sustainability for water and sanitation has been given by Grafton et al. (2015) who examine how water is managed in urban environments in a sustainable manner, see figure 2.3. The definition includes sustainability of infrastructure submissive to biosphere's and society's sustainability, providing a platform for economical sustainability. Sustainability can also be defined by Sustainable Development Goals (SDG's) from 2015 by United Nations as targets to reach by 2030 as a follow up on the Millenium Development Goals (MDG's). The relevant SDG's defining sustainability in relation to this study are:

- Goal number 6: Ensure availability and sustainable management of water and sanitation for all.
- Goal number 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
- Goal number 11: Make cities and human settlements inclusive, safe, resilient and sustainable.

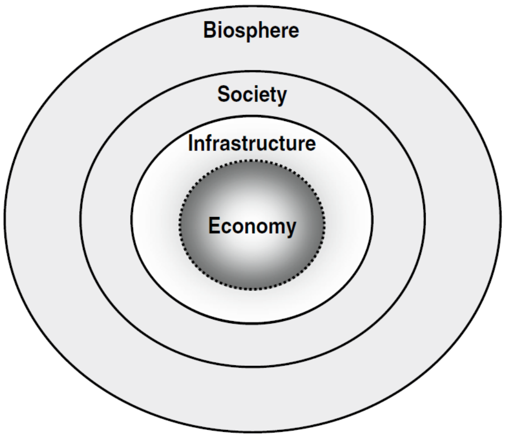

Figure 2.3: Sustainability by Grafton et al. (2015)

- Goal number 11: Ensure sustainable consumption and production patterns.

The definition of analysis is to conduct a procedure where a substantial whole is broken down into parts, and then followed by a synthesis where the separated elements are combined to form a coherent whole. To analyse and define sustainability of a system or a development, a framework with criteria and indicators for each criterium has be established. In order to recognise and develop optimal indicators for source separated sewer systems it is necessary to review prior research on sustainability analysis in the area of water and infrastructure systems. Multiple research groups have developed, created and suggested frameworks and criteria that can potentially be used as a foundation for analysing the sustainability of source separated sewage systems. Research by Balkema et al. (2002), Malmqvist et al. (2006), and Siew, Balatbat, and Carmichael (2016) among others are reviewed as theoretical background.

2.4.1 Framework and criteria

Balkema et al. (2002) analysed four methodologies for sustainability assessment of wastewater treatment. Sustainable technology is defined as technology that is not threatening quantity or quality, including diversity, of environmental resources. Flexible and subject to change with given time and space. According to authors sustainability can be assessed in various ways through single indicators (e.g. exergy analysis, economic analysis), environmental impact (e.g. LCA) or system analysis with multiple indicators for assessment (e.g. MCA). Another framework considered for the study is by Siew, Balatbat, and Carmichael (2016), who propose an alternative framework and method from the commercial assessment frameworks typically used in infrastructure development.

This framework is described according to Y. J. Siew, C. A. Balatbat, and

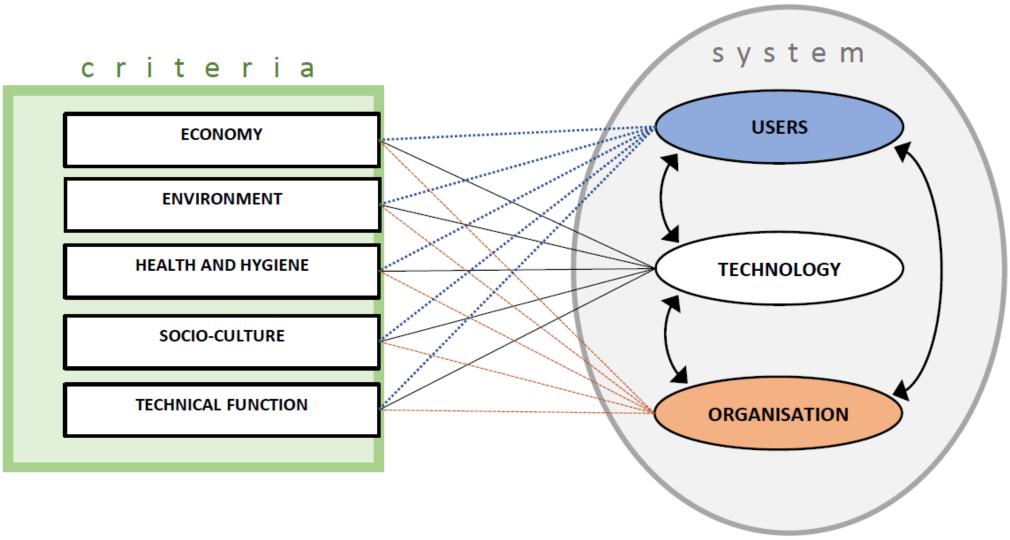

Figure 2.4: Interaction of system aspects and criteria for sustainability assessment. Adapted from Malmqvist et al., 2006

G. Carmichael (2013) to consist of six elements:
(1) systems-based criteria selection;
(2) quantitative measurement scales for criteria;
(3) characterizing each criterion by a measure of central tendency and dispersion;
(4) the distinction of additionality;
(5) criteria weighting; and
(6) combining criteria to give an overall score characterised by a measure of central tendency and a measure of dispersion.

Sustainability criteria for selection and comparison of sanitation systems are listed by Hellström, Jeppsson, and Kärrman (2000), Malmqvist et al. (2006), and Bracken et al. (2006), as health, environment, economy, socio-culture and technical function. The framework for systems analysis of sustainable urban water management by Hellström, Jeppsson, and Kärrman (2000) gives an approach on how to assess sustainability of technical systems of infrastructure. This framework is built on the requirements of Sustainable Urban Water Management - programme by Swedish Foundation for Strategic Environmental Research (MISTRA) that gives following supplementary requirements for water system. A water system should:
(a) have a high degree of functional robustness and flexibility,
(b) be adapted to local conditions and
(c) be easy to understand and thus encourage responsible behavior by the users.

As a reference to appreciate the task of system analysis, a list of eight practical sustainability criteria/indicators and the method for evaluation as proposed by Hellström, Jeppsson, and Kärrman (2000) are presented in table 2.4. Many of the meth-

Table 2.4: Priority set of criteria and method for evaluation according to Hellström, Jeppsson, and Kärrman (2000)

Citerion	**Method for evaluation**
Health and hygiene criterion	
Risk for infection	Microbial risk assessment
Social and cultural criterion	
Acceptance	Action research and assessment scales
Environmental criteria	
Eutrophication Spreading of toxic compounds to water, spreading of toxic compounds to arable soil, use of natural resources	Life-cycle assessment, computer-based modeling, material-flow analysis, and exergy analysis
Economical criterion	
Total cost	Cost-benefit analysis
Functional and technical criterion	
Robustness	Functional risk analysis

ods for evaluation specified here can be described to require extensive research and amount of data. Any of the mentioned, for example economic cost-benefit analyses, are common and widely accepted subjects for whole theses.

2.4.2 Indicators

The sewer system as a whole can be seen to provide a service, which is the primary goal of any kind of system: to provide an optimal service in a sustainable manner. Thus the reason for defining criteria, requirements and indicators is essentially to measure the service provided by the sewer system. Optimal service can further be judged by using specific indicators that have been defined by many for various occasions and studies. For example, for water supply evaluation industry standard performance indicators (PIs) have been defined by Alegre et al. (2016). Lindholm and Nordeide (2000) researched the relevance of criteria for stormwater system sustainability and suggested that while time taken to gather data correlates with accuracy of results, the number of indicators should remain low in order to optimise the usability of a method.

Different indicator frameworks for wastewater systems have been defined by Matos et al. (2003b), Schilling (n.d.), and Lindholm and Nordeide (2000), however no industry standard exists. The framework of indicators by Matos et al. (2003b) is divided into five categories: environmental indicators (1), operational indicators(2), quality of service indicators (3), physical indicators (4), and economic and financial indicators (5). Requirements for selecting representative performance indicators for these categories as described by Matos et al. (2003a) include: clear definitions of indicators, keeping number of indicators low, presentation of whole system, unbiased and truthful, no overlapping, practicable, auditable, defined by time, defined spatially. The authors highlight that using too few indicators risk misleading through push-pull effect, often occurring when improvement in one area is linked to deterioration in another. Another framework of indicators is defined by "European Fifth Framework programme: Computer aided rehabilitation of sewers and storm water networks (CARE-S)" It established a framework for prioritising sewer rehabilitation based on performance assessment (Schilling, n.d.). Care-S performance criteria are: environmental, operational, quality of service, economic and financial, and physical.

2.4.3 Weighting and scoring

Comparing specific criteria and indicators established for differing systems can be done through scoring and applying specific weighting to emphasise the overall importance of specific wanted properties. Index can thus be formed from an indicator. Scoring indices and weighting has been researched by Lindholm, Greatorex, and Paruch (2007) who studied sustainability indicators for alternative urban infrastructure systems. According to authors the need for practical methods to compare sustainability of urban infrastructure alternatives is huge, but care has to be taken as weighting used will lead to significant consequences for the result. Methods proposed by Lindholm, Greatorex, and Paruch (2007) to normalize sustainability indicator values include the following: Aggregating all indicators either to group indices or into one system index. Use of a reference system to establish a zero level in specific case, for example nature-based sewerage system as a reference system for conventional wastewater system.

Three levels of aggregation by Lindholm, Greatorex, and Paruch (2007):

- Level 1: Unaggerated level, if no weighting is done and indicators handled separately.
- Level 2: Grouping naturally connected indicators together: Ecological indicators, economic indicators and social indicators in separate groups allowing a group index to be calculated.
- Level 3: All indicators weighted into one index, from level 2 or directly from level 1.

Example methodology for comparing system alternatives by weighting an scoring comes from Gothenburg city (Sweden) where system study was used to analyse and find a sustainable future wastewater and bio-waste management system (Göteborgs Kretsloppskontoret, 2007). The applied method was a structured system study according to the conceptual framework by Malmqvist et al. (2006). Scoring was done by grading the different options on a scale of 0-4 on each indicator, where 4 was highest grade. Comparison of different criteria between alternatives was not seen possible, and system alternatives were compared only inside the same criteria. All aspects were included in a multi-criteria analysis (MCA) and weighted according to their importance to the city of Gothenburg and the stakeholders. Weighting of criteria was done by dividing a total sum of 100 between all criteria, and weighting of indicators was done by dividing a total sum of 100 between all indicators inside a criteria. (Göteborgs Kretsloppskontoret, 2007)

3
Method

Chosen method for the case study is a Multi Criteria Analysis (MCA) based on framework from previous research by Malmqvist et al. (2006) and Kärrman et al. (2012) as presented in section 2.4. The method is defined by Malmqvist et al. (2006): The conceptual framework utilizes a structured system study by dividing a studied system into subsystems of technology, organisation, and users which are then analysed against set sustainability criteria defined as health, environment, economy, socio-culture and technical function. See section 2.4.1 and figure 2.4 for description and graphical presentation of the chosen framework.

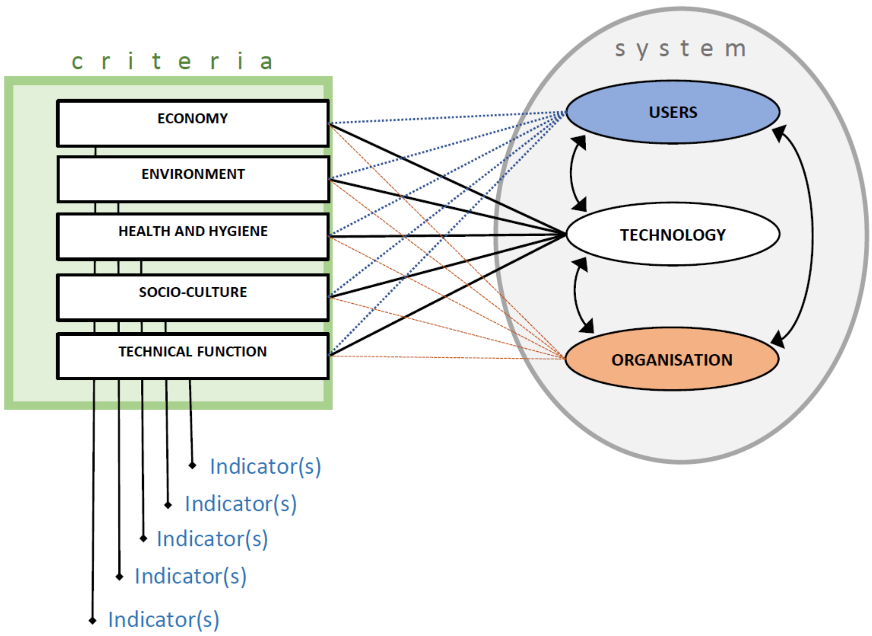

Figure 3.1: Sustainability of system, criteria and indicators adapted from Malmqvist et al. (2006)

This study concentrates on the subsystem of technology, but as interaction between subsystems is continuous, none of the subsystems can be neglected to provide a holistic assessment of sustainability. The approach chosen is to consider the impacts of a specific technology in a user and organisational setting. Sustainability is analyzed against the criteria of economy, environment, health and hygiene, socio-culture and technical function. To establish this, indicators for each criterion were chosen as presented in figure 3.1. Selection of indicator(s) for a given criterion is based on desk study and practical considerations of the case at hand. Theory considered as background for this is described in section 2.4.2.Indicator data could be obtained partly as directly applicable data from past projects but mostly refinement of data was necessary in order to establish comparable variables between the considered system alternatives (0-3). The refinement as part of data acquisition is considered part of the method and described in detail in following sections.

3.1 System alternatives

In order to compare and analyse the sustainability of different sewer solutions for blackwater for the case area the system alternatives are defined as:

- Alternative 0: (Reference) Closed tank collection system
- Alternative 1: Gravity sewer system
- Alternative 2: Low pressure sewer system
- Alternative 3: Vacuum sewer system

To define the alternatives many assumptions and decisions on system structure and components need to be made. While many factors influencing sustainability are defined by the specific environment where technology will be applied, there are likewise multiple factors that can be heavily influenced during design and construction process. An optimal solution is however very case dependent as multiple variables such as housing type, population density, choice of toilet type, topography, soil conditions etc. influence the outcome greatly. To establish a comparison with limited number of variables many of the fore mentioned factors were predefined in the following alternative descriptions. The factors not specifically predefined are assumed to remain constant for all the alternatives. The plan for the LPS system (appendix B, used as a basis for alternatives, is provided as a courtesy of Mälarenergi AB (Holmgren, 2017-01-18).

Assumptions related to all alternatives:

- Munga residental area consists of 280 households
- 112 properties for housing
- 168 properties for recreational use
- Population per household is 2.6 persons
- Blackwater volumes based on table 2.2
- Blackwater properties according to table 2.3

Household specific closed tank sewage collection system was chosen as a reference technology, as it was thought to full-fill the bare minimum requirements of all criteria for a sewer system. This technology has also been the chosen technology for studied case area of Munga for past decade (Wallsten, 2017). The chosen reference system was thus considered a feasible basic alternative when examining the characteristics of the peri-urban case study area as it also presents a common sewer system in majority of rural areas of Sweden (Jönsson, Nordberg, and Vinnerås, 2013).

3.1.1 Sewage tank system, Alternative 0

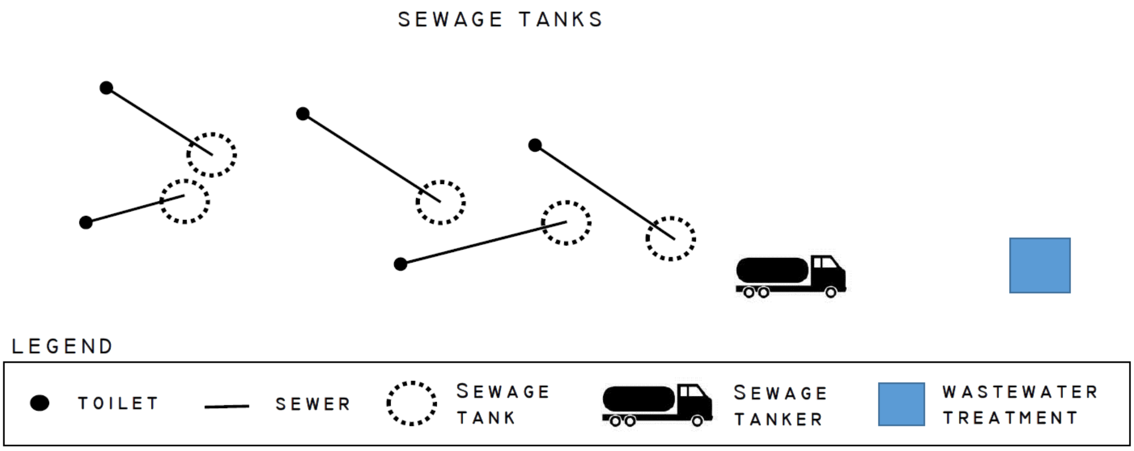

Figure 3.2: Schematic diagram of sewage tank system

The function of a closed sewage tank collection system relies on a gravity sewer connected to a private sewage tank, forming a closed system. Regular emptying of sewage tanks by a tanker truck and transportation to treatment facility is thus necessary. Besides the sewage tanker truck service function, all other considered system parts are private property.Figure 3.2 presents a schematic diagram of the system parts.

Components of the system defined and considered in this study include:

- Regular flushing toilets
- Household sewers leading to sewage tanks
- Sewage tanks for closed collection system
- Private vacuum truck service for transportation

The following further specification and assumptions are made for the system components of alternative 0:

- Toilets are conventional flushing toilets with flush volume 8.8 l/use

- Household sewer length is estimated to average 22 meters, 1/3 of the plot length,
- Sewage tanks are cylindrical in form and have a volume of 6.0 m^3
- Sewage tanks are emptied by vacuum truck service
- Vacuum truck capacity is 6.0 m^3 and average transport distance is 2 km
- Vacuum truck energy consumption is 8.2 MJ/ton* km transportation Sonesson (1996)

3.1.2 Gravity sewer system, Alternative 1

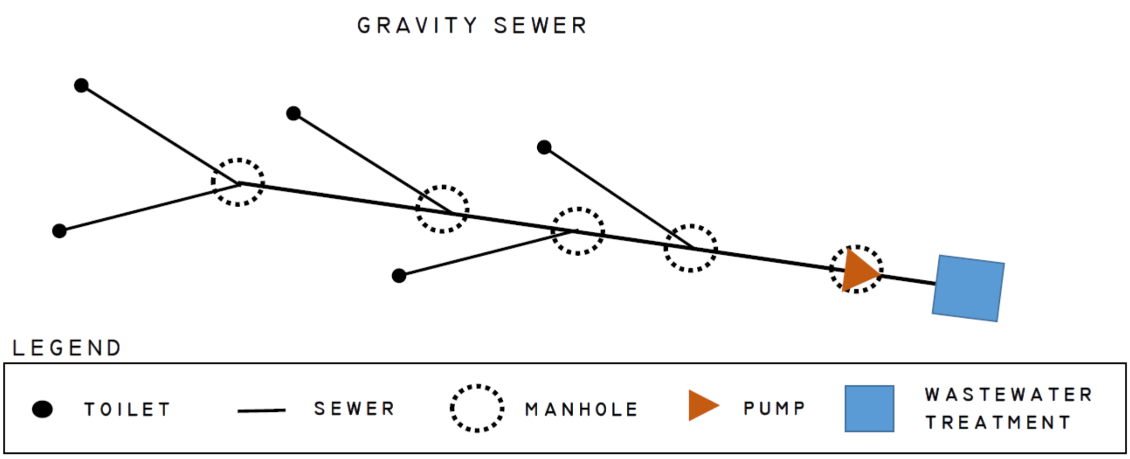

Figure 3.3: Schematic diagram of gravity sewer system

A wastewater collection system is often based on a gravitational force and an elevation gradient that transports wastewater from higher elevation to lower elevation in partially filled conduits. As gravity provides a free driving force for operation this is a common system that has been used for conventional wastewater systems since the first implementation of sewer systems. Even as a gravity system is mostly driven by force of gravity it is often necessary to pump wastewater part of the way as providing wastewater treatment for each natural drainage area is uneconomic and technically difficult to organise. (Butler, 2010). In most cases it is also required to lift wastewater at the treatment facility to succeed with treatment processes so wastewater pumping is inculded as a system component. Figure 3.3 presents a schematic diagram of the system parts.

Components of the system defined and considered in this study include:

- Toilets inside properties

- Household sewers leading to trunk network
- Trunk sewer network (interceptor)
- Pump stations with accessories
- Pressure transfer sewers to treatment facility

System plan presented in appendix A (Munga gravity system plan) functions as the basis of system specification. The following further specification is made for the system components of alternative 1:

- Toilets are conventional flushing toilets with flush volume 8.8 l/use
- Household sewer length is estimated to average 33 meters, 1/2 of the plot length
- Trunk sewer network length is based on the LPS system design for case Munga (appendix B) and is 10 800 meters
- Amount of pump stations needed for Munga is 9 pcs
- Pressure transfer pipeline length is 3230 meters

3.1.3 Low pressure sewer system, Alternative 2

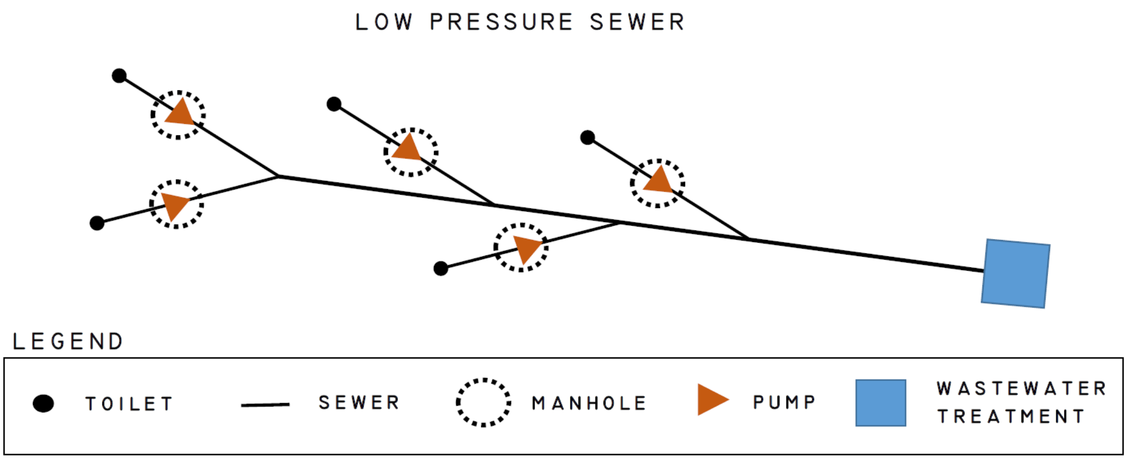

Figure 3.4: Schematic diagram of low pressure system

In a pressurized sewage collection system wastewater is driven by pressure gradient generated by pumping. For low pressure sewer (LPS) system pumping stations with single impeller centrifugal pumps can typically provide the needed pressure. Achievable maximum head of approximately 120 meters defines a low pressure system (Butler, 2010). Often a considerably lower pressure is sufficient to convey sewage and as pressure equals energy this is also desired. In Västerås, Munga LPS system has been selected for blackwater and the implemented design is presented in appendix B Munga LPS system plan (courtesy of MälarEnergi). Figure 3.4 presents a schematic diagram of the system parts.

Components of the system defined and considered in this study include:

- Toilets inside properties
- Household sewers to pump stations
- Household pump stations with accessories
- Pressure sewer network with accessories (i.e. valves)

The amount of data available in English for source separated blackwater systems operating with household specific pump stations (LPS). The practical considerations for theory are thus considered from experiences from conventional collection systems. According to Miszta-Kruk (2016) small household dedicated wastewater pumping stations were found most vulnerable and susceptible to failure and responsible for over 90% of all failure events in pressurized sewer systems studied, most of these failures (67%) were due to control unit break down.

System plan presented in appendix B (Munga LPS system plan) functions as the basis of system specification. The following further specification is made for the system components of alternative 2:

- Toilets are conventional flushing toilets with flush volume 8.8 l/use
- Household sewer length is estimated to average 22 meters, 1/3 of the plot length
- Pump sizing follows the design from the contractor SKT (see appendix B for pump Q-H curve)
- Number of household pump stations in the design equals the number of households (280 pcs)
- Trunk network length is 10 800 meters

3.1.4 Vacuum sewer system, Alternative 3

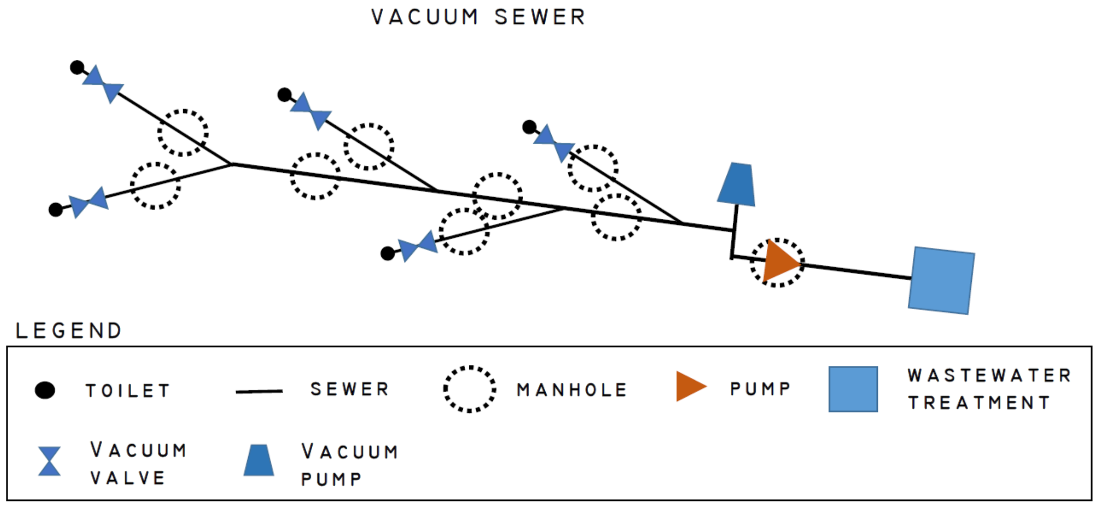

Figure 3.5: Schematic diagram of vacuum system

In vacuum collection system the medium is driven by pressure gradient generated by a vacuum station. There exists multiple variations of a vacuum sewer system, main difference being the location of vacuum interface. Vacuum collection system can be organised with interface valves integrated into toilet units, or separated into collection sumps, collecting all wastewater through gravity sewers much like in a LPS system. System considered in this study is of the former type and has vacuum interface at toilet level, expanding the vacuum network into housing units.

Figure 3.5 presents a schematic diagram of the system parts. The simplified function of a vacuum sewer system is as follows: When interface valve opens, the lower than atmospheric pressure (0.6 bar abs) in the pipeline drives the medium in a slug like form towards the vacuum pump station at a high velocity of 5-6 m/s. Through multiple interface valve openings and leakages in the system the slugs are transported to a vacuum collection tank. From the vacuum collection tank sewage is often transported onward to treatment with a low pressure system. (Butler, 2010, p.363)

Components of the system defined and considered in this study include:

- Vacuum toilets inside properties with interface valves
- Household vacuum sewers to trunk network
- Vacuum sewer network with accessories (i.e. flushing valves)
- Combined vacuum and pump stations complete with pumps and accessories

- Pressure transfer sewers to treatment facility

System plan presented in appendix C (Munga vacuum system plan) functions as the basis of further system specification. The following further specification is made for the system components of alternative 3:

- Toilets are vacuum toilets with flush volume 1.0 l/use
- Household sewer length is estimated to average 33 meters, 1/2 of the plot length
- Trunk sewer network length is based on the LPS system design for case Munga (appendix B) and is 10 800 meters
- Amount of combined vacuum and pump stations needed for Munga is 2 pcs
- Pressure transfer pipeline length is 1440 meters
- Vacuum system is assumed to require 15.0 kWh/(pe*a) for operation and save 3.5 kWh/(pe*a) by reducing flushing water consumption Remy and Jekel (2011)

Table 3.1: Chosen indicators for each criterion and respective unit

Criterion	Indicator	Unit
(1) Economic	(11) Investment cost	€
	(12) Operation cost	€
(2) Environmental	(21) Primary energy use for operation	kWh
	(22) Product quality as fertiliser	qualitative
	(23) Product ease of handling as fertiliser	qualitative
(3) Health and hygiene	(31) Risk for microbial infection	qualitative
(4) Socio-culture	(41) Education need for chosen system	qualitative
	(42) Maintenance need for households	qualitative
	(43) Risk of flooding	qualitative
(5) Technical function	(51) Expandability / adaptability	qualitative
	(52) Maintenance need for wastewater utility	qualitative
	(53) Risk of component failure	qualitative

The chosen indicators presented in table 3.1, are partly quantitative but mostly qualitative by nature. These indicators were deemed to support sustainability assessment of sewers in the chosen case study, as well as be applicable for similar projects within geographical boundaries of Sweden. The selection process was based on available data, practicality, and fore presented theoretical background. Implications of indicator selection are further discussed in section 4, Results and discussion.

The quantitative calculations are based on yearly blackwater production of the person equivalent (PE) from the case study area of Munga, Västerås. See introduction of area in section 2.1, and equation 3.1 for adjusted person equivalent. The 148 households (53%) labelled as recreational properties are transformed to permanent residencies with a usage percentage of 21,6% throughout the year (Kesämökit 2002. SVT. Tilastokeskus.) The 131 (47%) permanent residencies in the area and recreational properties transformed to permanent residencies result all-together into imaginary 163 households in the area. PE number for resulting households is formed with multiplier of 2.6 persons per household (Statistics Sweden: Average persons living in a single household dwelling, 2016).

$$PE_{tot} = PE_{recreational} + PE_{permanent} \tag{3.1}$$

Where,
PE_{tot} = Total adjusted person equivalent
$PE_{recreational}$ = Respective person equivalent according to usage percentage

$PE_{permanent}$ = Respective person equivalent according to usage percentage

Yearly blackwater flow Q_{BW} for PE of Munga was calculated dependant on toilet flush volume for alternatives specified in section 2.3 with equation 3.2. As the specified alternatives included different toilet types, Q_{BW} was calculated for both DFTs and VTs resulting in $Q_{BW,DFT}$ and $Q_{BW,VT}$. Data applied is specified in section 2.2.

$$Q_{BW} = Q_{TF} \cdot PE \tag{3.2}$$

Where,
Q_{TF} = Toilet Flush flow $[l/h \cdot pe^{-1}]$
Q_{BW} = Blackwater flow $[l/h]$

3.2 Economic criteria (1)

Indicator 11, Capital expenditure in MSEK was calculated by forming an investment cost by addition of system component values and construction costs. Values used for construction costs and system components for each system is largely based on *Urban Water* (n.d.), VeVa - tool for sustainability analysis of water and wastewater systems in transforming areas. The cost data was adjusted to value year 2016 by using construction cost index of Sweden (Statistics Sweden) (*Byggkostnadsutvecklingen index 1939=100. Korrigerad 2017-03-17* n.d.).

Cost data used for household components is based on a market overview by VA-guiden (*Marknadsöversikt 2016* n.d.). VA-guiden is an independent organisation promoting water and wastewater education and information sharing. Cost components for each alternative are specified in theory section 2.3. A total of 15% from total costs was considered to present design and project costs for each system alternative. The results for indicator 11 were further valued according to grading and scoring scale presented in figure 3.6 to establish a score from quantitative assessment.

COST(MSEK)	GRADE	SCORE
<32.5	very high	5
32.5-65	high	4
65-97.5	moderate	3
97.5-130	low	2
>130	very low	1

Figure 3.6: Grading and scoring scale for indicator 11

Indicator 12, Operation expenditure in kSEK was calculated through the energy use calculation added with annual maintenance costs. Cost data used for operation costs is based on *Urban Water* (n.d.), VeVa - tool for sustainability analysis of water and wastewater systems in transforming areas. The cost data was adjusted to value year 2016 by using the construction cost index of Sweden from Statistics Sweden (*Byggkostnadsutvecklingen index 1939=100. Korrigerad 2017-03-17* n.d.). As cost data was seen rather theoretical lacking consideration to practicality of construction an additional 25% construction marginal was added. Operation costs for system alternatives with pumping (0,2) and vacuum transport (3) are based on indicator 21, primary energy use of operation and electricity cost of 0.437 SEK/kWh (Statistics Sweden, 2013). No changes in electricity price over system lifetime was considered. The results for indicator 12 were further valued according to grading and scoring scale presented in figure 3.7 to establish a score from quantitative assessment.

COST(MSEK)	GRADE	SCORE
<2.5	very high	5
2.5-5	high	4
5-7.5	moderate	3
7.5-10	low	2
>10	very low	1

Figure 3.7: Grading and scoring scale for indicator 12

3.3 Environmental criteria (2)

Indicator 21, Primary energy use for operation, was considered in order to grasp which of the alternatives provide energy-wise the most sustainable solution. The base data was applied to blackwater volumes in each alternative according to equation 3.2. For alternatives 0 and 3 previous research data by Sonesson (1996) (section 3.1.1) and Remy and Jekel (2011) (section 3.1.4) was used, providing direct energy consumption. Equations used for calculating a rough estimation of operational energy use for alternatives 1 and 2 are specified in equation 3.3. Further equations E.1, E.2, E.3, E.4, E.5 and E.6 are detailed in appendix E. Pump head of 50 mwc was used for calculating pressure energy and a transport distance half of total network length as an average. Relative friction factor (ε) 1 mm was used to account for pipe friction losses developing over time within the sewer system and local head losses due to pipe bends, valves, intakes, outlets etc. Relative pipe roughness was defined as relative friction factor divided with pipe internal diameter $\frac{\varepsilon}{d}$. Completely turbulent flow regime was assumed with Reynolds number $(R_E)10^5$ and dynamic head-loss calculated according to D'Arcy equation using the Moody diagram (see appendix E for diagram) to determine Darcy-Weisbach friction factor (f = 0.01). Figure 3.8 shows grading and scoring scale for primary energy usage.

$$E_{tot} = \frac{E_{pot} + E_{kin} + E_{pre} + E_{loss}}{F_{eff}} \tag{3.3}$$

Where,
E_{tot} = Total Energy
E_{pot} = Potential Energy
E_{kin} = Kinetic Energy
E_{pre} = Pressure Energy
E_{loss} = Pressure Losses
F_{eff} = Efficiency factors

ENERGY [MWh]	GRADE	SCORE
<5	very high	5
5-10	high	4
10-15	moderate	3
15-20	low	2
>20	very low	1

Figure 3.8: Grading and scoring scale for indicator 21

Indicator 22, Product quality as fertiliser and indicator 23, ease of handling were considered as a qualitative indicators for environmental criteria. The most important aspect for product quality was considered to be phosphorus and dry matter concentration of blackwater as it affects the quantity and handling of fertiliser. Data was taken as average from three literature sources handling source separated blackwater in vacuum systems by Hertel et al. (2015), Tidåker et al. (2006), and Rohde (2016). See theory section, table 2.3 for details and data used.

For both indicators 22 and 23, average values for phosphorus concentration ($P_{avg,VT}$) and dry matter concentration ($DM_{avg,VT}$) were applied for system alternative 3 (vacuum) directly, and for alternatives 0-2 adjusted for same FU but larger produced volume of blackwater according to equations 3.4 and 3.5.

$$P_{conc} = \frac{Q_{BW,VT}}{Q_{BW,DFT}} \cdot P_{avg,VT} \tag{3.4}$$

Where,
P_{conc} = Phosphorus concentration in kg/ton^{-1}
$Q_{BW,VT}$ = Blackwater flow from vacuum toilets
$Q_{BW,DFT}$ = Blackwater flow from dual flush toilet systems
$P_{avg,VT}$ = Average phosphorus concentration from literature

$$DM_{conc} = \frac{Q_{BW,VT}}{Q_{BW,DFT}} \cdot DM_{avg,VT} \tag{3.5}$$

Where,
DM_{conc} = Dry matter concentration in kg/ton^{-1}
$Q_{BW,VT}$ = Blackwater flow from vacuum toilets
$Q_{BW,DFT}$ = Blackwater flow from dual flush toilet systems
$DM_{avg,VT}$ = Average dry matter concentration from literature

The results for indicators 22 and 23 were further defined according to grading and scoring scale presented in figures 3.9 3.10 to establish a score from qualitative assessment.

DM [mg/l]	GRADE	SCORE
>8	very high	5
6-8	high	4
4-6	moderate	3
2-4	low	2
<2	very low	1

Figure 3.9: Grading and scoring scale for indicator 22

P [mg/l]	GRADE	SCORE
>200	very high	5
150-200	high	4
100-150	moderate	3
50-100	low	2
<50	very low	1

Figure 3.10: Grading and scoring scale for indicator 23

3.4 Health and hygiene criteria (3)

The health and hygiene criterion is included by applying a qualitative microbial risk assessment (MRA) to analyse Indicator 31, Risk for microbial infection. Risk was determined as a product of probability and consequence of occurrence for each considered exposure pathway. Mechanisms of exposure were considered for each system alternative including as many mechanisms for users and maintenance personnel.

Point and mechanism of exposure for users:

- Toilet: Exposure during maintenance or use
- Surface water: Uncontrolled discharge from system
- Field crops: Unhygienic fertiliser

Point and mechanism of exposure for maintenance personnel:

- Toilet: Exposure during maintenance
- Tank/pipe system: Exposure during maintenance
- Truck/pump/vacuum station: Exposure during maintenance

Risk products were calculated for each mechanism by multiplying score from risk probability with risk consequence. Probability was scored with scale one to five: 1, less than once; 2, one to two times; 3, three to four times; 4, five to six times; 5, more than six times annually. Consequence was scored with scale one to five: 1, mild symptoms; 2, short day lasting symptoms; 3, week long symptoms; 4, month long symptoms; 5 permanent illness or death

Figure 3.11 presents the matrix used to form a risk product for the recognised risk mechanisms according to probability and consequence. Total risk was calculated as average from the sums of user and maintenance risks for each system alternative. and scored according to figure 3.12.

	Propability of occurence				
Consequence of occurence	< 1 / a	1...2 / a	3...4 /a	5...6 / a	> 6 / a
mild symptoms	1	2	3	4	5
short day lasting symptoms	2	4	6	8	10
week long symptoms	3	6	9	12	15
month long symptoms	4	8	12	16	20
permanent ilness or death	5	10	15	20	25

Figure 3.11: Microbial risk assessment matrix

SUM	RISK	SCORE
<7.5	very low	5
7.5-13.5	low	4
13.5-28.5	moderate	3
28.5-40.5	high	2
>40.5	very high	1

Figure 3.12: Grading and scoring scale for indicator 31

3.5 Socio-cultural criteria (4)

Selected qualitative indicators for criteria are

- *(41) Education need for chosen system*

- *(42) Maintenance need for households*
- *(43) Risk of flooding*

Education need (indicator 41) was included as qualitative assessment of education need, by applying multiple statements for each system alternative to form a comprehensive view on educational need that is bound to specific technology alternative. The general principle is that scoring follows the familiarity of system alternative as education need for current system applied as reference alternative gains maximal score due to lack of education need. Both user and operation perspective were considered for the same statements.

Test statements applied for indicator 41, education need from user and operator perspective:

- Need for guidance to implement and manage installation of system independently
- Need for guidance to start using/operating system correctly
- Amount of new procedures involved with use/operation
- Complexity of system working principle and operation
- Effort required for implementing system

Results for indicator 41 were further defined according to grading and scoring scale presented in figure 3.13 to establish a score from qualitative assessment.

ED NEED	GRADE	SCORE
very low	very high	5
low	high	4
moderate	moderate	3
high	low	2
very high	very low	1

Figure 3.13: Grading and scoring scale for indicator 41

Indicator 42, Maintenance need for households was included with aim to account for failure events that demand user attention and initiative to be taken and likewise events where entry inside household, and or property, can likely disturb users. Due to lack of available data specific on source separated sewer systems, data from mixed sewer systems was used as defined by Miszta-Kruk (2016).

Included failure points were:

- (0,1,2,3) household sewer
- (0) collection tank
- (1) connection chamber
- (3) vacuum interface

Event numbers were calculated according to failures per length of sewer and amount of units and valued according to figure 3.14.

MAINT NEED	GRADE	SCORE
<200	very high	5
200-400	high	4
400-600	moderate	3
600-800	low	2
>800	very low	1

Figure 3.14: Grading and scoring scale for indicator 42

Indicator 43, Risk of flooding was included as an indicator by applying a qualitative risk assessment for flooding with different system alternatives. Risk was determined as a product of probability and consequence of occurrence for each considered flooding mechanism. Mechanisms of flooding were considered for each system alternative in similar number. Risk products were calculated for each system alternative for the following points and mechanisms.

Points and mechanisms of flooding:

- Household sewer: Blockage and flooding
- Sewer/collection tank: Blockage and flooding
- Pump/vacuum station/truck: Operational malfunction/pump blockage

Figure 3.15 presents the matrix used to form a risk product for the recognised risk mechanisms according to probability and consequence. Risk products were calculated for each mechanism by multiplying score from risk probability between less than once annually (<1/a) and more than six annually (>6/a), with score from risk consequence, between one to five in severity. Single risk score then added up to form total product that was scored according to figure 3.16.

Risk consequences score and definitions were defined as:

1. single sewer surcharging
2. areal sewer surcharging
3. single household flooding
4. multiple households flooding
5. areal system wide flooding

	Propability of occurence				
Consequence of occurence	< 1 / a	1...2 / a	3...4 /a	5...6 / a	> 6 / a
single sewer surcharging	1	2	3	4	5
areal sewer surcharging	2	4	6	8	10
single household flooding	3	6	9	12	15
multiple households flooding	4	8	12	16	20
areal system wide flooding	5	10	15	20	25

Figure 3.15: Flooding risk assessment matrix

SUM	RISK	SCORE
<9	very low	5
9-15	low	4
15-30	moderate	3
30-45	high	2
>45	very high	1

Figure 3.16: Flooding risk assessment result scoring

3.6 Technical function criteria (5)

Selected indicators for criteria are

1. (51) Expandability / adaptability
2. (52) Maintenance need for wastewater utility
3. (53) Risk of component failure

Indicator 51, Expandability / adaptability was included to account for possible future alterations to system structure be it expansion through population growth or diminishing wastewater flow through degrowth of population. Technical consideration was done by judging the system alternatives against following statements:

- Consequence of diminishing population
- Consequence of growing population
- Possibility to alter treatment location
- Subsystems capable to operate independently
- Technical ease of adding/removing a sewer connection

Results for indicator 51 were further defined according to grading and scoring scale presented in figure 3.13 to establish a score from qualitative assessment.

DIFFICULTY	GRADE	SCORE
very low	very high	5
low	high	4
moderate	moderate	3
high	low	2
very high	very low	1

Figure 3.17: Grading and scoring scale for indicator 51

Indicator 52, Maintenance need for wastewater utility was included to account for maintenance events in the sewer network which are initiated and handled by the utility without interference from users. Much like for indicator 42, maintenance need for households, data availability specific from source separated sewer systems was poor, and data from mixed sewer systems was used as defined by Miszta-Kruk (2016).

To separate these events from indicator 42 focus was put on events in facilities of the system that are solely under utility's control and operation such as in:

- sewer mains
- pump stations
- vacuum stations

Event numbers were calculated according to failures per length of sewer and amount of units for each alternative and valued according to figure 3.18.

MAINT NEED	GRADE	SCORE
<30	very high	5
30-60	high	4
60-90	moderate	3
90-120	low	2
>120	very low	1

Figure 3.18: Grading and scoring scale for indicator 52

Indicator 53, Risk of component failure was included as an indicator by applying a qualitative risk assessment for different system alternatives. Risk was determined as a product of probability and consequence of occurrence for each considered failure mechanism. Mechanisms were considered for each system alternative in similar number. Risk products were calculated for each system alternative for the following points and mechanisms.

Points and mechanisms of failure:

- Toilet: Blockage
- Household sewer: Blockage
- Sewer main/collection tank: Leakage
- Pump/vacuum station/truck: Breakdown

Figure 3.15 presents the matrix used to form a risk product for the recognised risk mechanisms according to probability and consequence. Risk products were calculated for each mechanism by multiplying score from risk probability between less than once annually (<1/a) and more than six annually (>6/a), with score from risk consequence, between one to five in severity.

Risk consequences score and definitions were defined as:

1. single household affected
2. multiple households affected
3. prolonged daylong discrepancy
4. prolonged areal discrepancy
5. system failure for all users

Figure 3.19 presents the matrix used to assess the recognised risk events according to probability and consequence, while single risk scores were then added up to form total product that was scored according to figure 3.20 while

	Propability of occurence				
Consequence of occurence	< 1 / a	1...2 / a	3...4 /a	5...6 / a	> 6 / a
single household affected	1	2	3	4	5
multiple households affected	2	4	6	8	10
prolonged daylong discrepancy	3	6	9	12	15
prolonged areal discrepancy	4	8	12	16	20
system failure for all users	5	10	15	20	25

Figure 3.19: Component failure risk assessment matrix

SUM	RISK	SCORE
<9	very low	5
9-15	low	4
15-30	moderate	3
30-45	high	2
>45	very high	1

Figure 3.20: Grading and scoring scale for indicator 53

3.7 Multi-Criteria-Analysis and scenarios

Decided method applied for weighting of selected criteria and indicators was similar to Göteborgs Kretsloppskontoret (2007) presented in theoretical background. For this study included subsystems (criteria) according to theoretical framework were: Economic, Environmental, Health and hygiene, Socio-cultural and Technical function. For each considered system alternative aggregation of indicator scores was done to criteria level, by using weighting as well as total sustainability level, including all subsystems.

Weights applied were acquired through a questionnaire delivered to expert group involved in source separation project in Munga, Västerås (,for questionnaire see appendix D). This weighting was applied to scores formed for each indicator as described in detail in following sections for each subsystem. The scoring scale was selected to range from one to five describing 1, very low; 2, low; 3, moderate; 4, high; 5, very high grade for respectful indicator. Weighting scale for MCA according to questionnaire is presented in figure 3.21. The answer rate for the questionnaire was 3/8 (37,5%).

Criterion / Indicator	**Total weight**	
1 Economic	**15%**	
(11) Investment costs		6%
(12) Operational costs		9%
2 Environment	**28%**	
(21) Primary energy for operation		9%
(22) Product quality as fertiliser		11%
(23) Product ease of use as fertiliser		9%
3 Health and hygiene	**17%**	
(31) Risk for microbial infection		17%
4 Socio-culture	**20%**	
(41) Education need for chosen system		7%
(42) Maintenance need for households		9%
(43) Risk of flooding		4%
5 Technical function	**20%**	
(51) Expandability / adaptability		4%
(52) Maintenance need for wastewater utility		5%
(53) Risk of component failure		11%

Figure 3.21: Weighting for MCA according to questionnaire

Scenario 1 (even-weight scenario) analysis was performed, as the answer rate for weighting questionnaire was low and take size small. Scenario 1 was built with even weighting for all considered subsystems and indicators within them to test the sensitivity and effect of weighting. In this scenario all subsystems were given a weight of 20% and within subsystem (criteria) the weight was distributed evenly.

Scenario 2 (electric-truck) analysis was done to test applicability of the method for future situation where advances in truck transport technology would allow fossil fuels to be replaced by electricity. For scenario 2 original weighting was used to test outcome of MCA by changing input values for only alternative 0 (tank collection) for indicators 11 (Capex), 12 (Opex), and 21 (Primary energy consumption). Used values for electric truck transport were applied from Sen, Ercan, and Tatari (2017) and Zhao et al. (2016).

4

Results and discussion

The results and discussion chapter presents findings of the study for each studied sustainability subsystem criteria under its own section. Result tables are expanded with directly following discussion highlighting major finding with each indicator. Structure is seen efficient in conveying to reader much needed information on background factors and possible uncertainties influencing result. Results are strictly applicable only for case study area of Munga but discussion parts can be used as a valuable reference when considering similar system implementations in other areas in Sweden. The overall comparison between system alternatives is presented in section 4.6.

4.1 Economic criteria

Comparison of results in MSEK for alternatives with economic indicator 11, Capital expenditure are shown in table 4.1 together with weighted scoring. Results in MSEK during system lifetime and scoring for indicator 12, Operational expenditure are presented in table 4.2. For indicator 11 in table 4.1 the benefit of reference alternative 0, closed tank collection system over other alternatives is seen as expected but major finding inside economic criteria. As for alternative 1, gravity sewer system results show very high investments costs that are expected. For indicator 12 in table 4.2 otherwise rather even result between alternative shows high operational costs for alternative 0.

For capital expenditure indicator 11, results indicate anticipated and pronounced difference between extremes of tank collection system and gravity sewer system due difference with nonexistent and extensive network investment. Results imply

Table 4.1: Economic indicator 11, Capital expenditure results

Alternative	**Capex** [MSEK]	**Score**	**Weighted score**
Tank (0)	14.9	5	0.30
Gravity (1)	137.2	1	0.06
LPS (2)	78.7	3	0.18
Vacuum (3)	75.0	3	0.18

Table 4.2: Economic 12, Operational expenditure results

Alternative	**Opex** [MSEK]	**Score**	**Weighted score**
Tank (0)	82.8	1	0.09
Gravity (1)	0.4	5	0.45
LPS (2)	0.7	5	0.45
Vacuum (3)	0.5	5	0.45

gravity sewer applicability for Munga suffers most from steep alternating terrain, requiring multiple pump stations in addition to generally higher unit construction cost, due to stricter requirements constant slope and construction quality as pointed out by Water Environment Federation (2008) and Larsen et al. (2013) in section 2.3. Results show similarity when comparing gravity system to vacuum as Islam (2017), who suggests vacuum system to have 30% benefit over gravity, whilst study here shows 50% benefit. A closer look and scrutiny on elements such as valve pricing in vacuum system is neglected in the study and this is seen as a possible handicap and beneficial subject for further study.

For operational expenditure indicator 12, results seem at first hand rather extreme for tank collection system alternative. Method for obtaining cost may cause discrepancy as tank collection cost was evaluated as cost per truck transport for calculated volume as other cost data based on expenditure per person equivalent. Results are however supported by sheer logic of and linkage to energy consumption of truck transport with fossil energy source. While within network based alternatives 1, 2 and 3 the differences are clearly defined by energy use for transport of wastewater. Recognised further research is related to cost from transport at boundary between treatment and reuse in agriculture as highlighted by Kjerstadius (2017) among others. Unsustainable transport distance and volume of hygienic BW are recognised having potential to tilt economic comparison around and important further research area connected to source separated sewers.

4.2 Environmental criteria

Environmental indicators considered for system alternatives together with weighted scoring, are presented in following tables for 21, Primary energy use of operation in MWh/FU; 22, Product quality as fertiliser; 23, Ease of handling as fertiliser. For indicator 21, table 4.3 shows alternatives 0 and 2 yielded clearly higher yearly energy use than other system alternatives. For indicator 22, table 4.4 product quality results were logical and as predicted as they portray theoretical phosphorus concentration for produced BW, thus alternatives with dilute BW scored very low. Likewise for indicator 23, table 4.5 results indicate that dilute systems result in very low outcome for ease of handling due to vast volume of dilute sewage produced.

Table 4.3: Environmental indicator 21, Primary energy use of operation results

Alternative	**Primary energy use (op)** [MWh]	**Score**	**Weighted score**
Tank (0)	29.5	1	0.09
Gravity (1)	5.2	4	0.35
LPS (2)	14.4	3	0.26
Vacuum (3)	6.4	4	0.35

Table 4.4: Environmental indicator 22, Product quality as fertiliser results

Alternative	**Product quality**	**Score**	**Weighted score**
Tank (0)	very low	1	0.11
Gravity (1)	very low	1	0.11
LPS (2)	very low	1	0.11
Vacuum (3)	high	4	0.43

Table 4.5: Environmental indicator 23, Ease of handling as fertiliser results

Alternative	**Ease of handling**	**Score**	**Weighted score**
Tank (0)	very low	1	0.09
Gravity (1)	very low	1	0.09
LPS (2)	very low	1	0.09
Vacuum (3)	high	4	0.35

For indicator 21, major findings are substantially greater energy use for tank system, as well as LPS alternative compared to other network based sewer systems. Finding is supported by energy intensiveness of road transport and higher energy losses with pumping in longer and smaller diameter pipelines resulting in lower efficiency in comparison to systems with a centralised pumping approach and larger component size. Indicators 21 and 12, opex can be seen to slightly overlap as results show similar order between alternatives and indicator 12 includes energy pricing as a component. Recognised further research for indicator 21 is related to transport at boundary between treatment and reuse in agriculture as highlighted previously for economic criteria, section 4.1. Unsustainable transport distance and volume of hygienic BW are recognised having potential to overcome environmental benefits gained elsewhere in the sewer chain.

Method behind indicators 22 and 23 and its connection to flush amounts defined in section 2.2 can be considered problematic. Indicators show considerable overlapping due to this and neglect possibilities with reducing flushing amounts from conventional flush toilets. It is however shown that systems yielding high phosphorus concentration in blackwater yield also good environmental sustainability as volume required to be transported and spread on fields remains lower. Field handling and spreading of ready fertiliser was outside the scope of this study but considerable difference between alternatives exists due to five times better phosphorus to water -ratio and water to dry matter -ratio.

Above mentioned key finding is supported by research by Tidåker et al. (2006) as effect of dilution through flushing amounts and system design for collection were listed as main factors for environmental sustainability of blackwater systems. Yet another aspect for dilution comes from storage and treatment facilities, as according to Jönsson et al. (2005) this contributes in major way to energy use due to increased volumes and common treatment method which includes increasing sewage temperature to gain pathogen removal. Effects of treatment and spreading on sustainability are outside the scope of this work and present a recognised blind spot for overall sustainability of compared systems.

Impact of sewer construction on environmental criteria is not considered as overall effects were deemed minimal by research of Vahidi et al. (2016). However difference between alternatives is implied by different construction methods, mainly due to recommended pipeline profile: 0; no sewer main, 1; constant slope, 2; parallel to ground, and 3; saw-tooth profile. Here the major environmental benefit of re-using excavated material in respect to replacing with newly extracted materials found by Petit-Boix et al. (2016) could lift specially solutions powered by external pressure and independent on strict pipeline profile requirements. Further research is however required to cover implications on resources needed for construction.

Indicator selection for environment criteria is found to be partly overlapping. Push-pull effect between indicators as detailed by Matos et al. (2003a) in section 2.4.2 implies an insufficient number of independent indicators. Additional indicator recommended would be quantitative energy use per kg phosphorus reused and carbon dioxide emissions per kg phosphorus reused.

4.3 Health and hygiene criteria

Indicator considered for health and hygiene criteria was qualitative risk of microbial infection. Results for indicator 31, are shown in table 4.1 together with scoring. As key differences between alternatives it can be seen that two categories emerged lower risk for alternatives 1 and 3 and higher risk for alternatives 0, gravity and 2, LPS.

Table 4.6: Health and hygiene indicator 31, Risk of microbial infection results

Alternative	Risk of microbial infection	Score	Weighted score
Tank (0)	moderate	3	0.50
Gravity (1)	low	4	0.67
LPS (2)	moderate	3	0.50
Vacuum (3)	low	4	0.67

Comparison with indicator 31, risk analysis indicates increased risk for system alternatives with user participation in operations such as collection tank filling status in alternative 0 and low pressure pump station in alternative 2. When neglected this participation leads to risk of microbial infection by exposure to pathogens through these exposure points. Specific care with projects such as Munga need to be directed towards avoiding problems from potential exposure points such as collection tanks or pump wells with aid of automation, remote monitoring and set alarms in water utility's supervisory control and data acquisition (SCADA) system. Recognised limitations on the executed MRA are lack of relevant data from operating systems and set system boundary that does not consider function or method of BW treatment. Recommendation for further details of MRA are to apply data from pilot projects for source separated BW systems where the study may give basis to build on.

4.4 Socio-cultural criteria

Qualitative indicators considered for socio-cultural criteria were 41, Education need for chosen system; 42, Maintenance need in households; and 43, Risk of flooding. Result comparisons for indicators and system alternatives are shown in tables 4.7, 4.8 and 4.9. For indicator 41 results showed higher need for education and lower score for more technically advanced and complex system alternatives 2 and 3 compared to more commonly used simple technologies in alternatives 0 and 1. For indicator 42 systems relying heavily on user initiated maintenance as tank collection system alternative 0 scored considerably lower. For indicator 43 previous observation with user maintenance was pronounced with higher risk of flooding and lower score due to more likely occurrence.

Table 4.7: Socio-cultural indicator 41, General education need for system results

Alternative	Education need	Score	Weighted score
Tank (0)	very low	5	0.37
Gravity (1)	very low	5	0.37
LPS (2)	moderate	3	0.22
Vacuum (3)	very high	1	0.07

Table 4.8: Socio-cultural indicator 42, Maintenance need in households results

Alternative	**Maintenance need, households**	**Score**	**Weighted score**
Tank (0)	very high	1	0.09
Gravity (1)	moderate	3	0.26
LPS (2)	very low	5	0.43
Vacuum (3)	low	4	0.35

Table 4.9: Socio-cultural indicator 43, Risk of flooding results

Alternative	**43 Risk of flooding**	**Score**	**Weighted score**
Tank (0)	high	2	0.08
Gravity (1)	moderate	3	0.12
LPS (2)	moderate	3	0.12
Vacuum (3)	moderate	3	0.12

Both user and utility aspects were considered for indicator 41. The high education need for vacuum systems is based on the unfamiliarity and rareness of the technology in municipal sewage applications as it is considered an unconventional sewer system as defined in theory section 2 by Miszta-Kruk (2016). Key point found to affect education need is in-house sewer system renovation requiring comprehensive support to households for implementation. Conventional systems such as tank collection and gravity get higher score on education need, as little or concern to changes in toilet behaviour needs to be paid when using a gravity sewer system. As an example of further research a system alternative where the current existing system would implemented as part of a hybrid system should be studied. Thus existing in-house sewers would feed vacuum collection system via collection chambers, with vacuum interface replacing collection tanks.

For indicator 42 the low maintenance need for alternatives 2 & 3 is mostly due to maintenance that is in the network domain and thus falls under indicator 52, Utility maintenance need. Also it is notable that based on previous failure analysis research by Miszta-Kruk (2016) the small household units at the connection threshold seem dominant in maintenance need and failure amounts as compared to transfer lines and larger pump stations in any system. For alternative 0 the bulk of maintenance need is explained by continuous need of emptying the collection tanks.

For indicator 43 the results imply higher risk of flooding for alternative 0 with required user participation for collection tank supervision, very much like in case of indicator 31. This overlap can be seen as a major limitation on indicator 31 as they address largely same points and events of failure. Even though very local in nature flooding of collection tank is thought to be socially unsustainable and possible cause for stigmatisation of specific system. Further research in crustation build up and flooding for BW systems through large scale pilot experiments is needed and recommended to gain data and knowledge on how this affects large scale flooding risk.

4.5 Technical function criteria

Results for qualitative indicators considered for technical function criteria are presented in tables 4.10, 4.11 and 4.12. For indicator 51 results indicate high flexibility for simple system alternative 0 and low for complex system alternative 3. For indicator 52 results high score for alternative 0 where user initiated maintenance is key. For indicator 53 results showed high score for simple system and lower for higher complexity.

Table 4.10: Technical function indicator 51, Difficulty of expansion or contraction of system results

Alternative	**Expandability / adaptability**	**Score**	**Weighted score**
Tank (0)	high	4	0.16
Gravity (1)	moderate	3	0.12
LPS (2)	moderate	3	0.12
Vacuum (3)	low	2	0.08

Table 4.11: Technical function indicator 52, Maintenance need for utility results

Alternative	**Maintenance need, utility [qualitative]**	**Score**	**Weighted score**
Tank (0)	very low	5	0.23
Gravity (1)	moderate	3	0.09
LPS (2)	very high	1	0.05
Vacuum (3)	very low	5	0.23

Table 4.12: Technical function indicator 53, Risk of component failure results

Alternative	**Risk of component failure**	**Score**	**Weighted score**
Tank (0)	very low	4	0.45
Gravity (1)	low	3	0.34
LPS (2)	low	3	0.34
Vacuum (3)	low	3	0.34

The expandability and adaptability indicator 51 is of interest on many levels as it addresses the common need for updating and renewing the sewer system. Especially when considering diminishing sewage flows, common in many country-side regions, systems that do not rely heavily on volumes of water for conveying waste fraction show tremendous potential in terms of adaptability. In this aspect tank collection system gains advantage with ease of alterations as a single household system with new modules added or old ones removed without further consideration.

Maintenance need for the utility, indicator 52 is according to the results clearly heightened for the low pressure system. The simple reason for this network design where each household has its own pump station, adding up to theoretical 280 pump stations in Munga area. Research data according to Miszta-Kruk (2016) shows that household pumping stations have a high tendency for blockages. For this indicator limitation comes from overlap with indicator 42, maintenance need for in households.

Indicator 53 shows more complex systems introduce a higher risk of system failure as discovered in research by Göteborgs Kretsloppskontoret (2007) and Malmqvist et al. (2006). Analysing the risk of component failure and the output from the risk matrix the biggest difference comes not on the probability, but rather from the consequence. Where in network based systems, component failure leads to problems on a wide area and with multiple houses, the dedicated tank collection system bears poises consequences only to a single household. Limitation to indicators comes from risk of component failure (53) direct overlapping with maintenance need for water utility (52). As introduced in theory chapter according to Matos et al., 2003a this is not an optimal situation and results in pronounced influence of component failures for the total score. Overlapping is however contained inside a single sustainability criteria of Technical function (5). Challenge with evaluating non-existent systems based on literature data was in great part concentrated to technical function. Data on operational systems is scarce and mostly available from northern German vacuum systems by Rohde (2016), Otterpohl, Albold, and Oldenburg (1999), and Sievers et al. (2016).

4.6 Multi-Criteria-Analysis and scenarios

Overall result from weighted scores summarised for each criteria is presented in figure 4.1. In overall comparison alternative 3 vacuum system gains highest scoring after weighting procedure. Where more conventional sewer technologies gained higher marks for socio-cultural criteria, the unconventional vacuum system excels in the chosen environmental indicators. High score from MCA for the reference alternative 0, tank collection system is considered noteworthy result highlighting functional robustness of simple technical system as alternative.

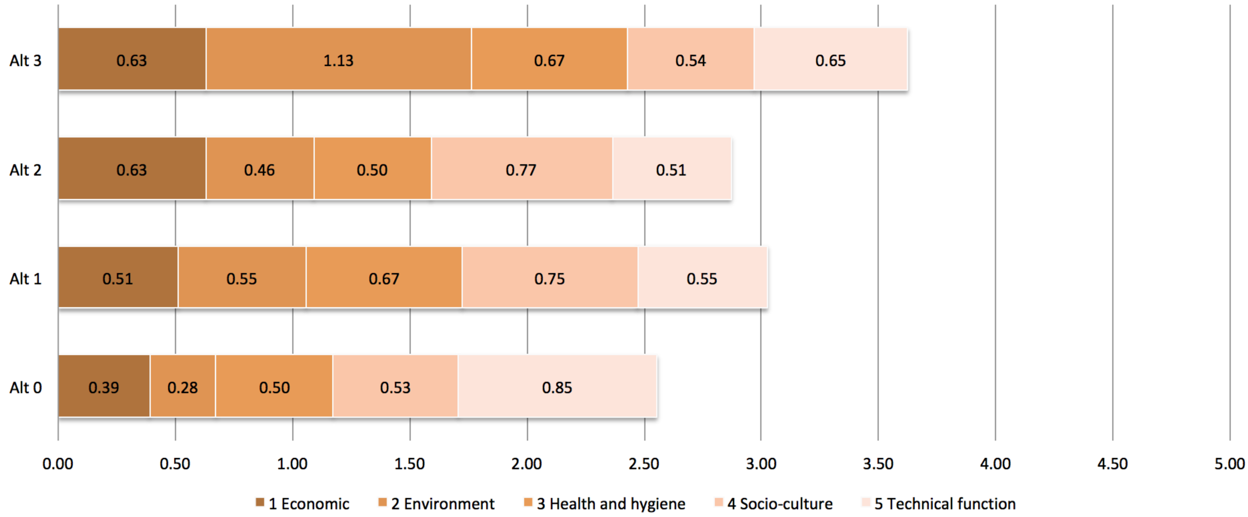

Figure 4.1: MCA results diagram

Explaining and supporting the high score of alternative 3 from weighting perspective is supported by reference to previously presented figure 3.21, which shows the strongest 28% weight given to Environmental criterion. This benefits vacuum system as it is the highest ranked alternative in environmental criterion before weighting. Results from overall MCA analysis are however subject to debate as they are based on weighting gained from one project group and narrow take size. Even within a project group influence from personal and professional preferences affect scoring and are likely to cause alteration in results depending on which persons participate in the weighting procedure.

The results from the scenario 1 (even-weight), presented in figure 4.2) however support findings as only internal changes in results are detected while the order of alternatives remains the same. By weighting all subsystems and indicators evenly a clear difference is seen as this effect especially economic and environmental subsystem index scores. It is to be noted that even in scenario 1 a singular indicator gains a high overall weight in the case of criteria 3 (Health and hygiene), where only 1 indicator presents the criteria. The effect from indicator selection and distribution hereby affects the end-result considerably.

Scenario analysis by applying electric truck BE on transportation in alternative 0, provides an interesting result: outcome of MCA by changing input values for only alternative 0 (tank collection) for indicators 12 (Opex), and 21 (Primary energy consumption). Research by Sen, Ercan, and Tatari (2017) and Zhao et al. (2016) suggests that electric truck transport may provide an environmentally sustainable solution only if energy production is done in a sustainable way. In the scenario 2 analysis results, presented in figure 4.3, alternative 0 benefits greatly in Environmental criteria through improvement from result in indicator 21 (Primary energy consumption). However electric truck transport provides very little benefit over indicator 12) operation cost, due to massive volume of transport and costs com-

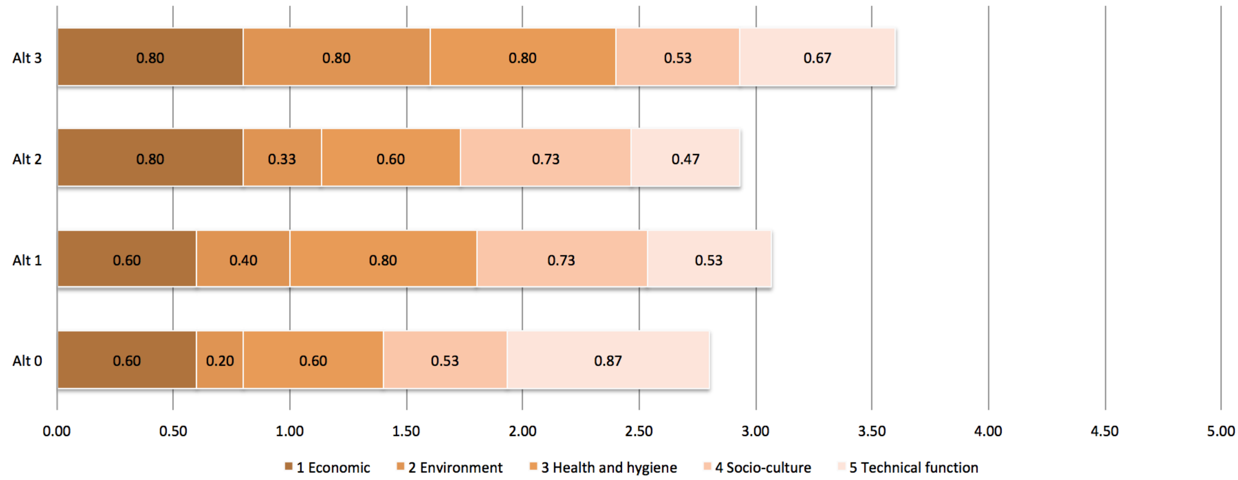

Figure 4.2: MCA scenario 1, even-weight results diagram

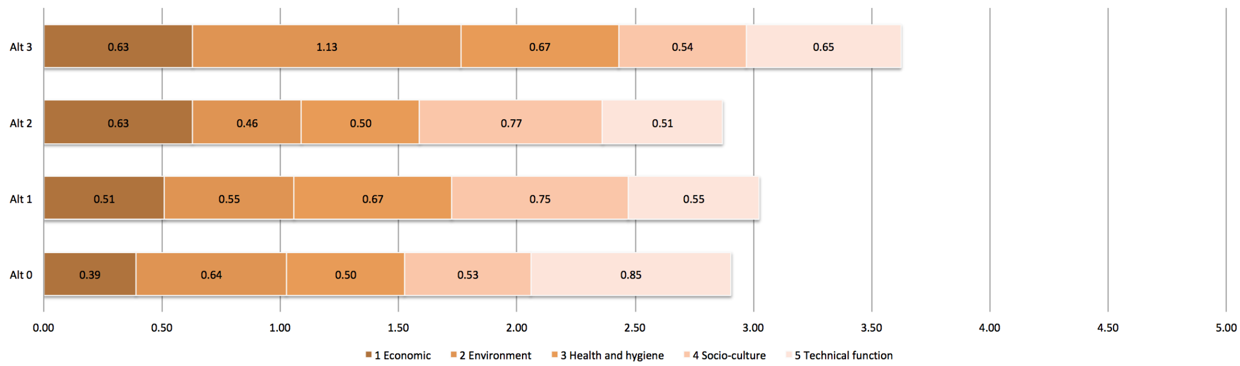

Figure 4.3: MCA scenario 2, electric-truck results diagram

pared to other alternatives. Results portray substantial potential with electric truck transport but are limited to primary energy use. Secondary effects and especially environmental effect from carbon dioxide emissions should be considered carefully if alternative 0 is considered.

4.7 Method evaluation and recommendation

Considering the overall applicability of this study, a major limitation stems from the delimitation and defined system boundary (Lindholm and Nordeide, 2000). Treatment of blackwater sewage and transport of effluent to agricultural reuse are outside the scope of this study. Results show that produced blackwater volumes differ greatly between alternatives which implies a difference exists as well outside the system boundary (ie. treatment and transport). The hypothesised effect on overall sustainability outside the system boundary is larger energy need for maintaining constant process temperature, and energy use for transportation, due to larger volumes of blackwater observed for alternatives 0 to 2. Further research on applying low flush technologies to reduce BW volume, and difference in treatment for the mentioned alternatives is needed.

Another limitation on accuracy of the study results is thought to arise from the chosen method and indicators. Suggested tools for evaluating sustainability criteria according to chosen framework in chapter 2.4.1 as defined by Hellström, Jeppsson, and Kärrman (2000) include for environmental criteria are: life-cycle assessment, computer-based modelling, material-flow analysis, and exergy analysis. Author agrees fully that mentioned tools would are recommended to gain a more in-depth view of sustainability but were considered too complex for the scope of this study. The aim and objectives of this study are considered to be satisfactorily fulfilled by a sustainability analysis of more holistic nature, as presented in this report.

Contradictory to contents and description of the chosen framework technology and user aspects of system alternatives were considered in more detail over organisational aspect that was by most part neglected. Reasoning behind this was both the recognised research gap, highlighting lack of technical know-how on source separating systems. Considering organisation aspect as integral part of this sustainability study might influence the result, lifting conservative technology alternatives that organisations are commonly used to operate. This would however be counterproductive as resistance of implementing new technology from an organisation could possibly undermine and limit further research and application of new rising technologies in pilot stages. Education of organisation, careful design, and correct technical solutions required for all alternatives despite selected technology are seen as best remedies to guarantee a functional sewer system and overcome prejudice.

Major problematic over the course of this study was applying industry standard indicators, such as performance assessment indicators CARE-S presented in section 2.4.2, on source separated sewers as these are targeted for a) Existent, operational systems and b) Conventional sewer systems. Another encountered problematic was found with applying existent data as garbage grinders and organic material are commonly in many pilot projects mixed with blackwater and possible cause for crustation and blockages. For peri-urban area such as Munga where no grinders are implemented the effects of this fraction should be neglected, but strictly relevant data was scarce.

Author highlights the need of further research and data collection on the effect of grinders on sewer function from various pilot scale installations, of which many are being implemented at time of writing in Sweden. Practical data such as maintenance of sewers (used method and frequency), blockages (amount per pipe km), together with analysis results of blackwater composition should be collected. To form a more detailed view of subsystem and indicator importance the weighting procedure should be repeated in a more extensive form. This could be established by extending the questionnaire to various existing pilot projects in northern Germany as well as Swedish pilot projects. Indicator selection is considered crucial for a successful future analyses and for this it is suggested that a more extensive array of indicators should be subjected to weighting procedure providing participants a possibility to dismiss irrelevant or overlapping indicators.

5
Conclusion

To address the main research question sewer system alternatives were defined for a case study and analysed with multi-criteria analysis. The devised set of sustainability indicators were aggregated for each alternative to single system index and sub-indexes within five aspects of sustainability: economic, environmental, health and hygiene, socio-cultural, and technical sustainability. Key points of knowledge drawn from this research are:

- Vacuum system is a serious contender for LPS system in peri-urban area such as Munga as low dilution of blackwater seems to benefit all other sustainability criteria covered in study except socio-cultural criteria where user-toilet nexus inflicts lowers score
- Sustainability is heavily dependant on valued aspects of that are partly inherited from the chosen framework and influenced by indicator selection and not only by weighting of multi-criteria analysis.
- Minor differences between pilot projects, such as grinder/no grinder or toilet type used, affect blackwater quality and quantity and present a considerable challenge to applying available research data on blackwater systems.

Suggestions for future research include:

- Array of indicators for sewer system sustainability subjected to weighting and evaluation of existing source separation pilot project users and staff
- First hand experience and data collection for prioritised indicators from implemented pilot projects
- Further on a development of flexible hybrid system alternative applicable for peri-urban areas utilising existing infrastructure as part of the collection network

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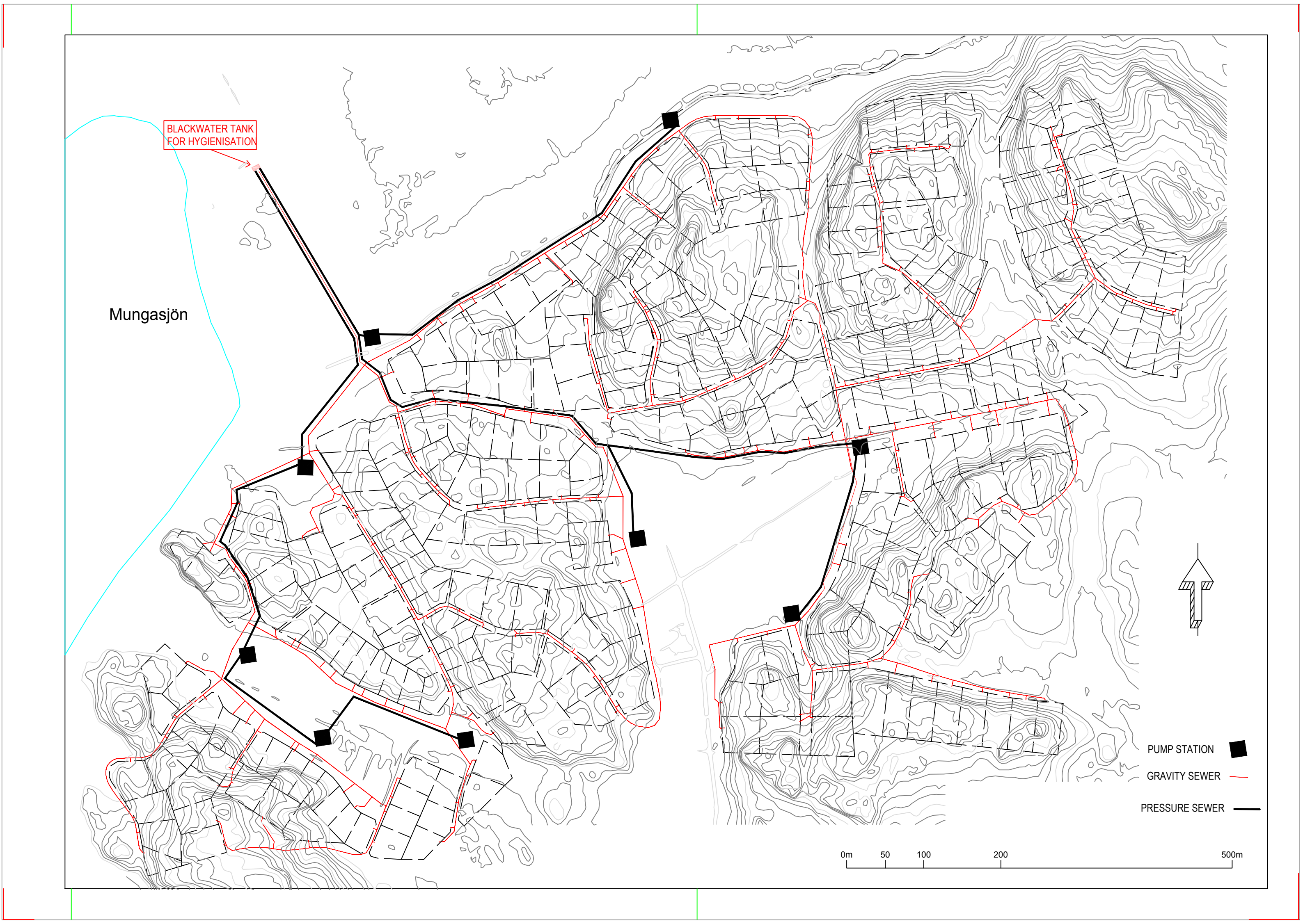
A

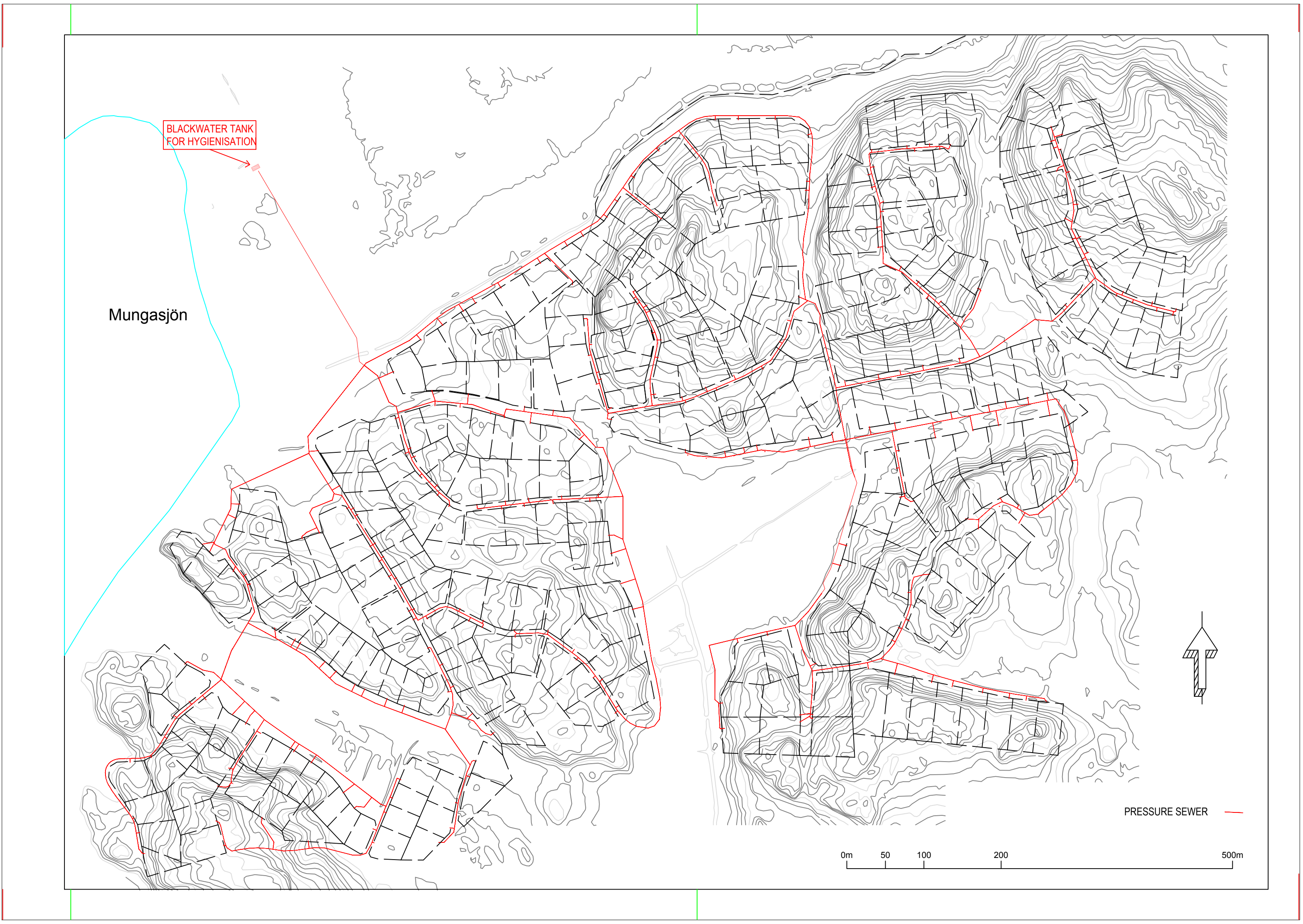
Munga gravity sewer system plan

A. Munga gravity sewer system plan



B

Munga LPS system plan


BLACKWATER TANK
FOR HYGIENISATION
Mungasjön
PRESSURE SEWER
0m
50
100
200
500m

SKT, LPS2000 screw impeller pump used for pump stations. Motor power: 1 kW, 230 VAC (1-stage), 50 Hz, 1450 rpm, 47 kg. Height of pump tank 2,6 m and diameter 0,65 m

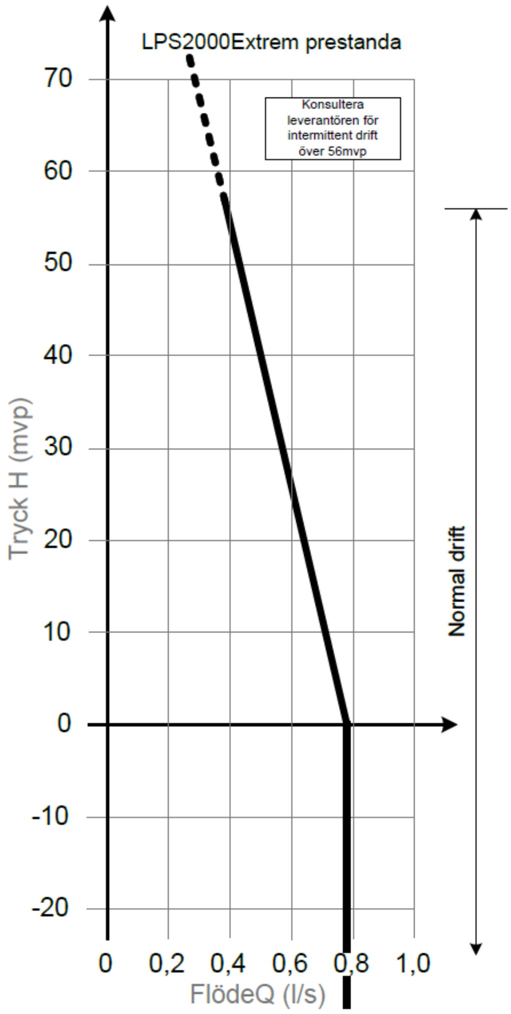
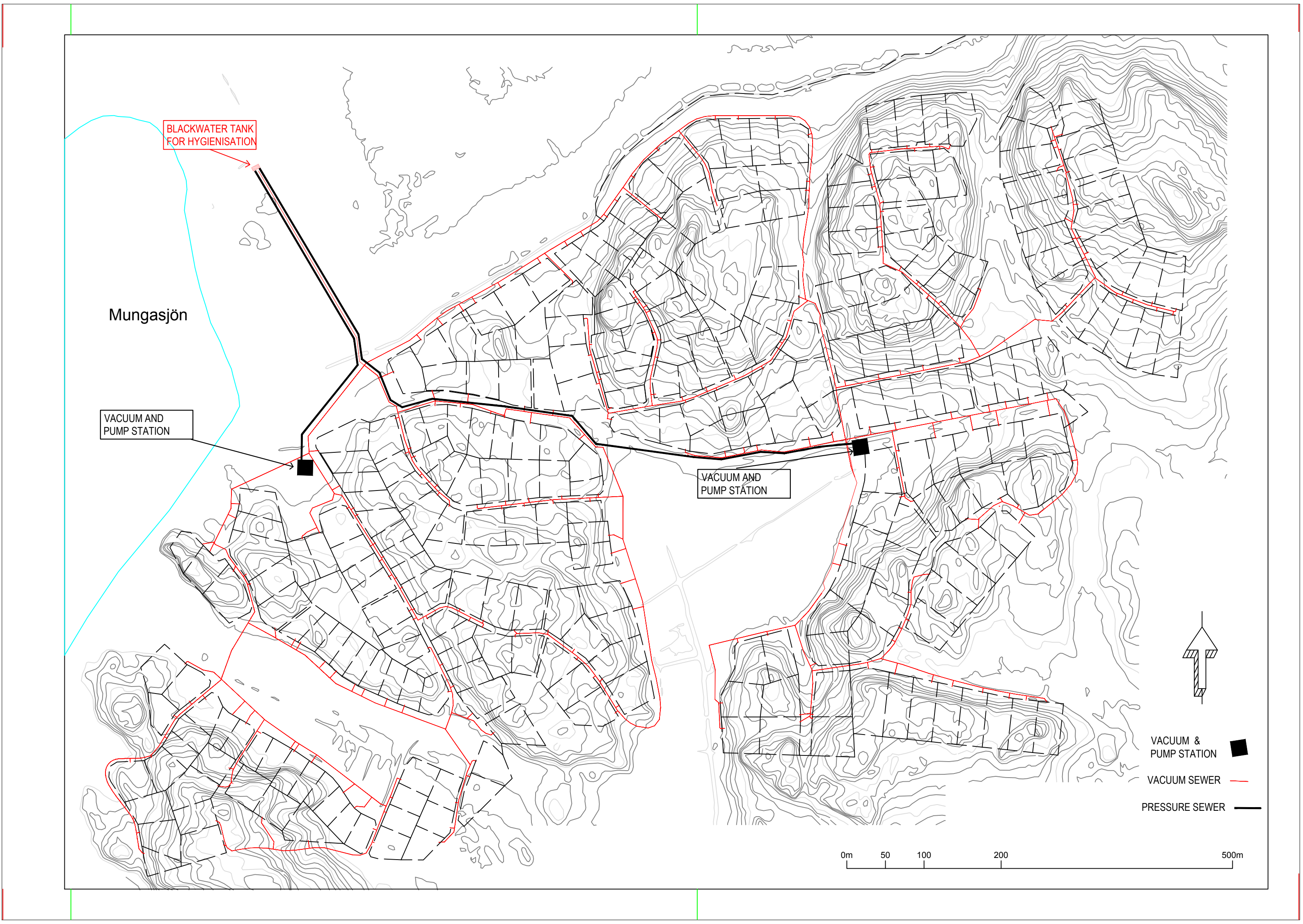


Figure B.1: LPS2000 pump Q-H curve

C

Munga vacuum system plan


BLACKWATER TANK
FOR HYGIENISATION
Mungasjön
VACUUM AND
PUMP STATION
VACUUM AND
PUMP STATION
VACUUM &
PUMP STATION
VACUUM SEWER
PRESSURE SEWER
0m
50
100
200
500m

D

Questionnaire

This is a questionnaire directed to project group related to source separation of blackwater in Munga, Västerås. The respondents are asked to kindly submit their answers in one week ***by Monday 2017-06-05.***

The aim of this questionnaire is to gather views from persons informed in development, design and operation of sewers for source separated blackwater to get a feel on which aspects of sustainability are most important to them when considering the project area of Munga. *Greywater sewers* are not part of the thesis scope, and *should not be considered* by the respondents.

The overall aim of the thesis is to analyze sustainability of the specified sewer alternatives and conduct a case study on pilot project area Munga in Västerås to determine which factors essentially affect the overall sustainability. The focus of the thesis is on technical aspects of the sewer system but considering views of organization and users. Figure 1 presents the criteria and indicators used in the thesis.

Criterion	Indicator	Unit
(1) Economic	(11) Investment cost	€
	(12) Operation cost	€
(2) Environmental	(21) Primary energy use for operation	kWh
	(22) Product quality as fertiliser	P_{tot}
	(23) Product ease of handling as fertiliser	qualitative
(3) Health and hygiene	(31) Risk for microbial infection	qualitative
(4) Socio-culture	(41) Education need for chosen system	qualitative
	(42) Maintenance need for households	qualitative
	(43) Risk of flooding	qualitative
(5) Technical function	(51) Expandability / adaptability	qualitative
	(52) Maintenance need for wastewater utility	qualitative
	(53) Risk of component failure	qualitative

Figur 1 Selected indicators for each criterion

Weighting:

The criteria are to be weighted by dividing a total score of 100 between the criteria. The weight given to individual criteria is thus between 0 (negligible importance) and 100 (only criteria of importance), and sum of weights for all criteria equals 100. Following table 1 is for criteria weighting.

The listed indicators are to be weighted by applying similar logic and dividing a total score of 100 inside each criterion between the indicators. The weight given to individual indicator is thus between 0 (negligible importance) and 100 (only indicator of importance), and sum of weights for all indicators inside each criteria equals 100. Following tables 2-6 are for indicator weighting.

Table 1. Criteria weighting (0-100, sum=100)

Criterion	1 Economic	2 Environmental	3 Health and hygiene	4 Socio-culture	5 Technical function
Weight					

Table 2 Economic indicators weighting (0-100, sum=100)

Indicator	11 Investment cost	12 Operation cost
Weight		

Table 3 Environmental indicators weighting (0-100, sum=100)

Indicator	21 Primary energy use for operation	22 Product quality fertiliser	23 Product ease of handling as fertiliser
Weight			

Table 4 Health and hygiene indicators weighting (0-100, sum=100)

Indicator	31 Risk of microbial infection
Weight	

Table 5 Socio-culture indicators weighting (0-100, sum=100)

Indicator	41 Education need for chosen system	42 Maintenance need for households	43 Risk of flooding
Weight			

Table 6 Technical function indicators weighting (0-100, sum=100)

Indicator	51 Expandability / adaptability	52 Maintenance need for wastewater utility	53 Risk of component failure
Weight			

With friendly greetings,
Ville Tanskanen

E

Equations

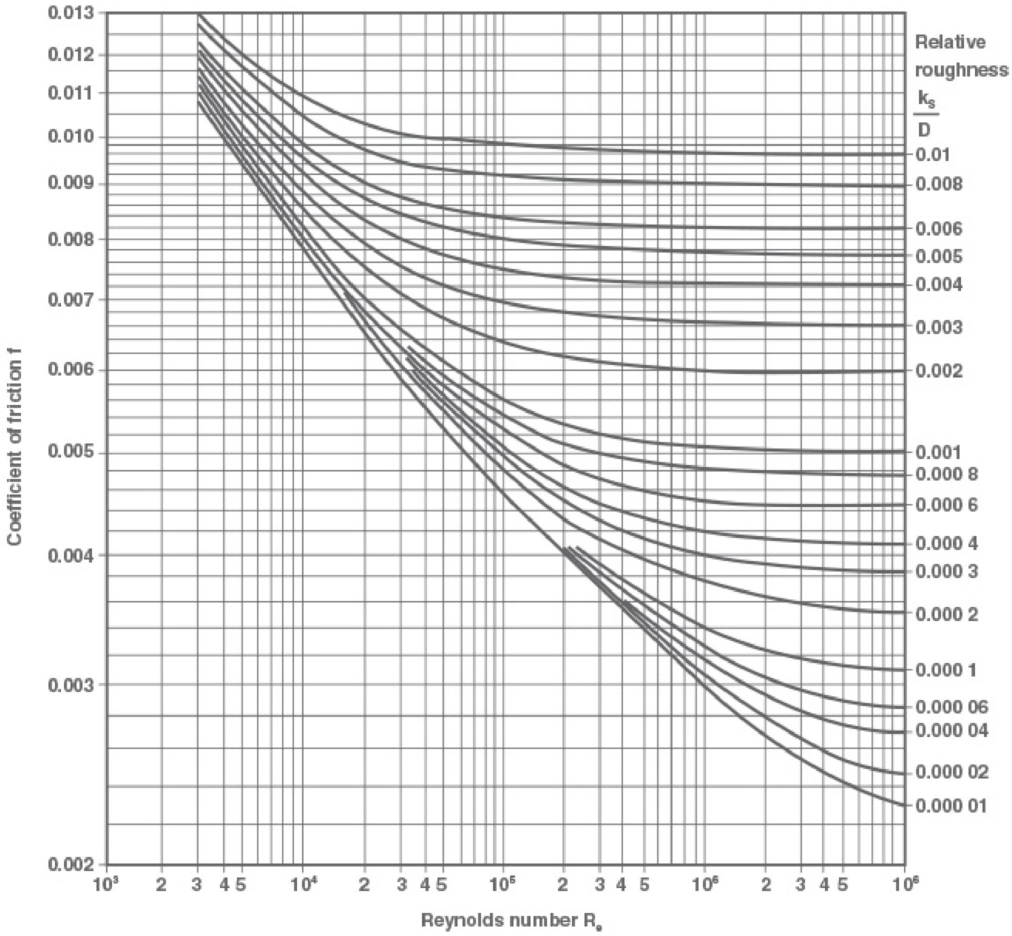


Figure E.1: Moody diagram

$$m_{BW} = Q_{BW} \cdot \rho_{BW} \tag{E.1}$$

Where,

ρ_{BW} = Density of blackwater [kg/l]
m_{BW} = Blackwater mass [kg]

$$u = \frac{Q_{BW}}{\frac{1}{4}\pi D^2 \cdot 3600 \cdot 10^6} \tag{E.2}$$

Where,
u = Flow velocity [m/s]
Q_{BW} = Blackwater flow [l/h]
D = Pipe inner diameter [mm] = 50

$$h_f = \frac{4fLu^2}{2gD} \cdot 10^3 \tag{E.3}$$

Where
H_f = Friction head loss [mmWC*]
L = pipe length [m]
u = flow velocity [m/s]
D = pipe internal diameter
* $1mmWC \approx 10Pa$

$$H = H_{geod} + H_f \tag{E.4}$$

Where
H = Hydraulic head [mmWC*]
H_{geod} = Geodetic head [mmWC*]

$$E_h = (m_{BW} \cdot g \cdot H_{geod}) + H_f \tag{E.5}$$

Where
E_h = Operational hydraulic energy need [kWh]
g = Gravitational acceleration [m/s^2]
The total primary energy needed for operation is calculated with energy efficiency assumptions:
η_{hydr} = 0.7
η_{elec} = 0.9

$$E_{op} = \eta_{hydr} \cdot \eta_{elec} \cdot E_h \tag{E.6}$$

Where
E_{op} = Operational energy need [kWh]