TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

MARIKA MÄKINEN

OPERATION OF VACUUM SEWER SYSTEM – CASE ONDANGWA, NAMIBIA

Master of Science Thesis

Examiners: Professor Jukka Rintala,
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ABSTRACT

MARIKA MÄKINEN: Operation of Vacuum Sewer System – Case Ondangwa, Namibia
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The purpose of this thesis was to analyze the malfunctioning vacuum sewer system in Ondangwa, Namibia. The system did not form adequate vacuum to transport sewage from the formation place to the vacuum station and therefore the collection chambers were flooding. The aim was to find the failures that caused malfunctioning, causes of the failures and solutions for the failures. In addition, four other vacuum sewer systems in Namibia were studied for comparison purposes. They were located in Gobabis, Henties Bay, Kalkrand and Stampriet. A two month field trip was done in Namibia in October and November 2014 and three methods were used to analyze the vacuum sewer systems in Namibia. The methods were literature survey, semi-structured interview and observation.

The vacuum sewer system in Ondangwa has faced many failures since the beginning of the design phase in 2006 until November 2014. The failures have been related to the vacuum pumps, vacuum sewers and collection chambers. There had been issues also during the design and construction phases. Majority of the failures have been caused by external factors (vandalism, misuse of the system and poor maintenance). However, the system is also difficult to maintain in the local conditions and material defect of the vacuum sewer system has also caused failures: the valve controllers break down easily when they are in touch with moisture. The impacts of the failures have exposed users and operators of the system to health risks and environment to contamination due to the sewage on the streets. The failures and the causes of the failures in the other vacuum sewer systems in Namibia have been very similar with the system in Ondangwa. The system in Henties Bay had the least amount of failures and the vacuum sewer system in Ondangwa had the biggest amount of failures. In November 2014 the system in Ondangwa did not operate anymore due to broken vacuum pumps.

Ondangwa and the four other LA's of Namibia have two options. They should either invest a lot on the improvement of the vacuum sewer systems or replace them with more applicable sewer systems. For example gravity sewer system is more familiar technology to the sewer system operators and users in Namibia. However, the improvement of the maintenance and protection of the system and education of the users is essential with gravity, vacuum or any other system. Otherwise vandalism and inadequate maintenance will cause failures also in the future, no matter what system is operating. The vacuum sewer system operation can be improved by fixing all the failures with proper materials and by proper contractors. The findings of this thesis are useful for improving the poor sanitation situation in Ondangwa and in the four other LA's.

TIIVISTELMÄ

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Diplomityön tarkoituksena on analysoida Pohjois-Namibiassa Ondangwan kaupungissa sijaitseva virheellisesti toimiva alipaineviemärijärjestelmä. Kyseisessä järjestelmässä alipaine oli liian alhainen. Sen vuoksi jätevettä ei saatu kuljetettua syntypaikalta alipainekeskukseen vaan se valui keräilysäiliöistä kaduille. Tavoitteena on löytää alipaineviemärin viat, vikojen aiheuttajat ja tarjota ratkaisuja vioille. Ondangwan lisäksi alipaineviemärijärjestelmä on käytössä myös muutamassa muussa Namibian kunnassa. Ondangwan alipaineviemärijärjestelmää verrattiin neljän muun Namibian kunnan (Gobabis, Henties Bay, Kalkrand ja Stampriet) virheellisesti toimiviin alipaineviemärijärjestelmiin. Alipaineviemärijärjestelmien vikojen syitä ja vikoja vertailtiin keskenään. Loka-marraskuussa 2014 tehtiin kahden kuukauden kenttätutkimus Namibiassa. Aineistonhankintaan käytettiin kolmea menetelmää: arkistojen tutkimista, haastatteluja ja havainnointia.

Tulosten perusteella Ondangwan alipaineviemäröintijärjestelmän viat alkoivat suunnitteluvaiheessa 2006 ja ovat jatkuneet marraskuuhun 2014 asti. Viat ovat liittyneet alipainepumppuihin, alipaineviemäriputkistoihin ja keräilysäiliöihin. Myös suunnittelu- ja rakennusvaiheessa tapahtui virheitä. Suurin osa vioista on johtunut ulkoisista tekijöistä (ilkivalta, väärinkäyttö ja puutteellinen kunnossapito). Alipaineviemärijärjestelmän kunnossapito on vaikeaa Namibian olosuhteissa ja epäkohdat alipaineviemärijärjestelmässä ovat myös aiheuttaneet vikoja: venttiilin säädin vioittuu herkästi joutuessaan kosketuksiin kosteuden kanssa aiheuttaen liian vähäistä alipainetta järjestelmässä tai jäteveden tulvimista keräilysäiliöistä kadulle. Viat ja vikojen aiheuttajat Gobabiksen, Henties Bayn, Kalkrandin ja Stamprietin järjestelmissä ovat olleet suhteellisen samanlaisia kuin Ondangwan järjestelmässä. Alipaineviemärien viat ovat altistaneet käyttäjät sekä kunnossapitäjät terveysriskeille ja ympäristön saastumiselle.

Ondangwalla sekä neljällä muulla analysoidulla Namibian kunnalla on kaksi vaihtoehtoa: nykyisten alipaineviemärijärjestelmien toiminnan kehittäminen tai järjestelmien korvaaminen toisella viemäröintijärjestelmällä. Esimerkiksi viettoviemäri on kunnossapitohenkilökunnalle ja käyttäjille tutumpi vaihtoehto kuin alipaineviemäri. Kummankin vaihtoehdon kannalta on tärkeää kehittää kunnossapitoa, kouluttaa käyttäjät ja suojata järjestelmä ilkivallalta. Muutoin ilkivalta ja puutteellinen kunnossapito aiheuttavat jatkossakin vikoja riippumatta siitä onko käytössä alipaineviemäri, viettoviemäri vai jokin muu järjestelmä. Alipaineviemärijärjestelmän toimintaa voi kehittää muun muassa korjaamalla kaikki viat laadukkailla materiaaleilla osaavien rakentajien toimesta. Diplomityön tuloksia voidaan käyttää avuksi sanitaatiotilanteen kehittämiseen Ondagwassa sekä neljässä muussa Namibian kunnassa joissa on alipaineviemäri.

PREFACE

This thesis was done as a part of development co-operation project called Partnership for Local Democracy & Development and Social Innovation (PLDDSI) between Namibia and Finland. Participants of the project were two municipalities in Namibia (Keetmanshoop and Ondangwa) and two municipalities in Finland (Lempäälä and Kangasala).

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Tampere, 12th of May 2016

Marika Mäkinen

CONTENTS

ABBREVIATIONS

A/L	Air to Liquid
CSA	Consulting Services Africa
C_v	Flow Coefficient Factor
DN	Diameter Nominal
DRFN	Desert Research Foundation of Namibia
EAAC	Electronic Air Admission Control
HDPE	High Density Polyethylene
H_f	Friction Head
H_s	Static Head
H_v	Vacuum Head
LA	Local Authority
NamWater	Namibia Water Corporation Ltd
NPSH	Net Positive Suction Head
PE	Polyethylene
PE-MD	Polyethylene, Medium Density
PF	Peaking Factor
PMS	Preferred Management Services
PVC	Polyvinyl Chloride
STD	Standard Dimension Ratio
STEP	Septic Tank Effluent Pump
TDH	Total Dynamic Head
V_o	Operating Volume of the Vacuum Tank
V_p	Piping System Volume
V_{rt}	Reservoir Tank Volume
V_t	Total System Volume
V_{vt}	Total Volume of the Vacuum Tank
VAT	Value Added Tax
Q_a	Station Average Flow
Q_{ave}	Average Daily Flow
Q_{dp}	Discharge Pump Capacity
Q_{max}	Peak Flow
Q_{min}	Station Minimum Flow
Q_{vp}	Vacuum Pump Capacity

1. INTRODUCTION

Vacuum sewer system is a sewage collection system for domestic wastewater. The main operating principle of vacuum sewer system is to transport sewage by differential air pressure (Water Environment Federation, 2008). The pressure differential is generated in a central vacuum station by vacuum pumps (Miszta-Kruk, 2015). Three main components of the system are collection chambers, vacuum sewer line and vacuum station (PDH engineer, 2007). Typically vacuum sewer systems are used when the construction of conventional gravity sewer system is not applicable for economical or technical reasons. However, vacuum sewer system can also co-operate with gravity sewer systems (Królikowska et al., 2013).

Average number of connections per vacuum sewer system is about 200 - 500 (Water Environment Federation, 2008) and typical length of vacuum sewer system is 2 - 4 km (Sekisui Chemical, 2015). Vacuum sewer system has a limited capability to transport sewage uphill and therefore it is recommended for flat or gently rolling ground (Jones et al., 2001). Besides of the transport of domestic wastewater there are also other applicable areas for vacuum sewer systems such as passenger airplanes and ships (Miszta-Kruk, 2015).

The first vacuum type wastewater collection system was patented already in 1888 in the United States by Adrian LeMarquand. The name of the system was ”the system of wastewater collection by barometric depression” (Miszta-Kruk, 2015). Early vacuum sewer system had consistent operational failures. Typical failures were too small vacuum mains, too large liquid slug volumes and insufficient air resulting in sewage transport failures. In addition, the system components neither were fully reliable. In 1980s significant improvements of the technology took place. Saw-tooth profile, improved valve controller, larger pipes and larger vacuum pumps were developed. The improvement of the system has continued until the present day. Today’s vacuum sewer systems are significantly different than the systems of the 1970s (Water Environment Federation, 2008). However, still today challenges are experienced with vacuum sewer systems.

One of the countries that use vacuum sewer systems for collection of domestic wastewater is Namibia. Vacuum sewer systems have been installed in several Local Authorities (LA) in Namibia. One of the systems was installed in 2006 - 2010 to Ondangwa, North-Namibia. Vacuum sewer system was selected to Ondangwa due to the flat soil and cheaper cost compared to gravity sewer system. However, in 2014 the vacuum sewer system in Ondangwa was malfunctioning. The system did not form adequate vacuum to transport the sewage from the formation place to the vacuum station and therefore the collection chambers were flooding.

The aims and objectives of this thesis is to analyze the vacuum sewer system located in Ondangwa and give recommendations for the future operation of the system. The analysis includes studying the main components of the system, finding the main failures of the system and the main causes of the failures. In addition, for this thesis was visited four other LA's (Gobabis, Henties Bay, Kalkrand and Stampriet) to get knowledge about the vacuum sewer system in Namibia and for comparison purpose with the Ondangwa system.

Chapter 2 presents the theory part of this thesis and introduces the vacuum sewer system technology. Chapter 3 presents the materials and methods of this thesis. It was done two months fieldtrip to Namibia in October and November 2014 to work in Ondangwa Town Council. During the field trip it was used three methods that are literature surveys, semi-structured interviews and observations.

Chapters 4 and 5 introduce the results regarding operation of the vacuum sewer systems in Ondangwa and in Gobabis, Henties Bay, Kalkrand and Stampriet. It is presented the main components of the vacuum sewer system in Ondangwa, and failures of the vacuum sewer system. In addition, the results will present the failures of the vacuum sewer systems located in Gobabis, Henties Bay, Kalkrand and Stampriet. Chapter 6 and 7 presents the discussion and conclusion of this thesis. In discussion are given recommendations for the future operation of the system and the results are compared to other studies.

2. VACUUM SEWER SYSTEM

2.1 Theory of Operation

The main operating principle of vacuum sewer system (Figure 1) is to transport sewage by differential air pressure from the formation place (houses) to the vacuum station. The main components of the vacuum sewer system are vacuum station, vacuum sewer line and vacuum station (Water Environment Federation, 2008).

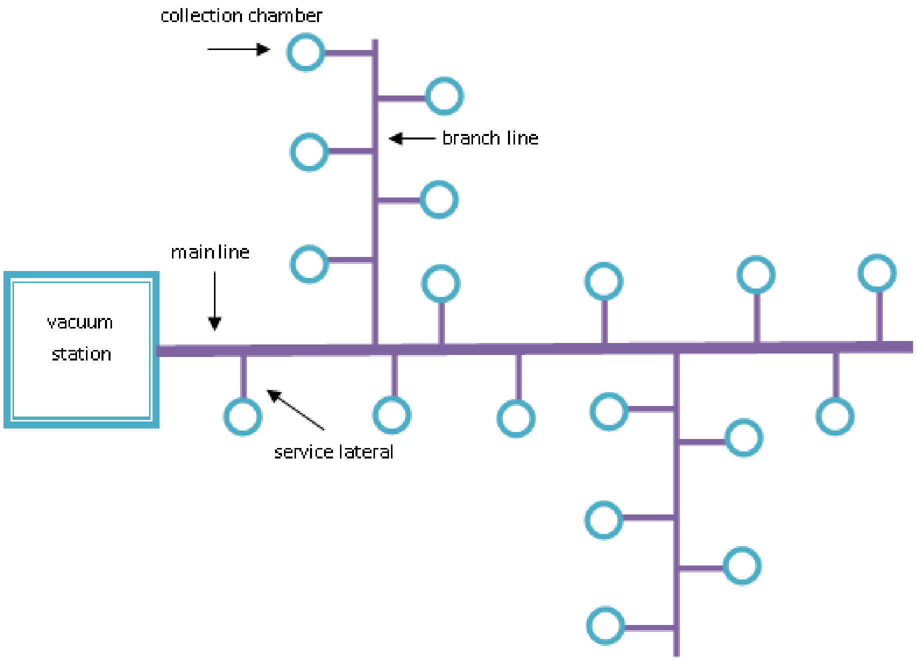

Figure 1. *Main components of the vacuum sewer system (modified from Water Environment Federation, 2008).*

First the sewage is drained by gravity from houses to the collection chambers. From collection chambers the sewage is transported by the differential air pressure through vacuum sewerlines to the vacuum station. Finally, from the vacuum station the sewage is pumped to a conventional system or to treatment facilities (Li et al., 2010; Werner et al., 2005).

2.1.1 Collection Chambers

The sewage is first drained by gravity from a formation place (house) to the sump of the nearby located collection chamber (Figure 2) (Bilfinger Berger, 2011). Collection chamber has two main purposes: to collect the sewage from the houses and to act as an energy input by letting atmospheric air enter the vacuum sewer lines and create differential air pressure (PDH engineer, 2007). The design of the collection chambers vary between the manufacturers.

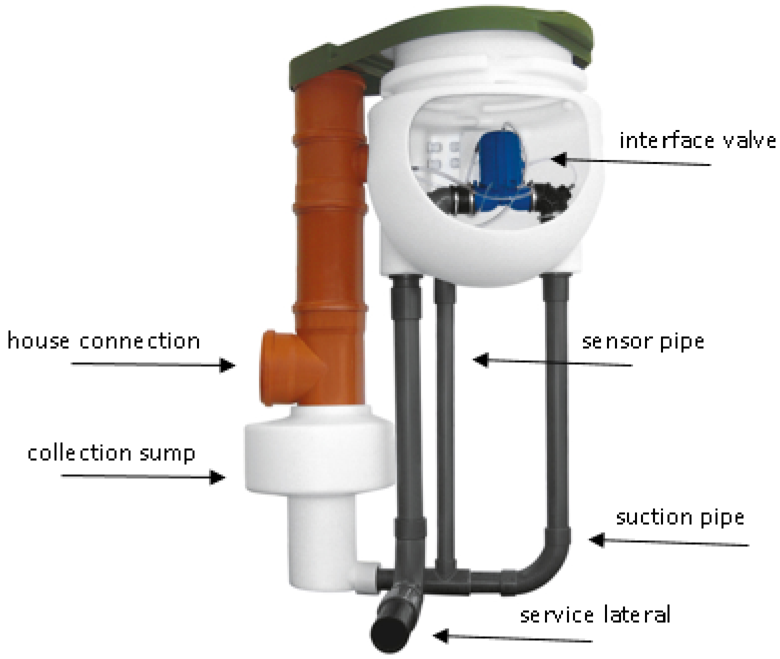

Figure 2. *Roediger collection chamber (modified from Roediger Collection Chambers, 2016).*

The main components of collection chambers are valve chamber (houses the valve), collection sump (accepts sewage from the house connection), interface valve, pneumatic valve controller, suction pipe (evacuates the sump), sensor pipe (transfers the rising sump pressure to the valve controller), house connection, service lateral (connects collection chamber to the vacuum sewer line) and covering lid (PDH engineer, 2007). The collection chamber can be divided into two main parts: the top part where the interface valve is located and the lower part where the sump is located (Masteller & Moler, Inc., 2013; PDH engineer, 2007). The two parts are sealed from each other's (EPA, 1991).

House connection is a gravity line between a house and a collection chamber (Little, 2004). Sewage flows from the house through the house connection to the collection sump that is a container that receives the sewage from the house. The sewage contains all the wastewater formed in the house (PDH engineer, 2007).

When a predetermined amount of sewage has accumulated to the collection sump, an interface valve opens automatically without a need of electricity (Bilfinger Berger, 2011; Little, 2004; Water Environment Federation, 2008) and pass the content of the sump and after that atmospheric air to the vacuum sewer line. Suction line is a component of the collection chamber that is used for evacuating the sump (PDH engineer, 2007) and the interface valve (pneumatic regulating valve) connects the collection chambers to the vacuum sewerline (EPA, 1991; Werner et al., 2005). Besides of a collection chamber, the interface valve can also be located in a specific vacuum toilet (EPA, 1991).

Normally the interface valve is closed in order to seal the vacuum sewer line and to continuously maintain negative pressure in the sewer line. In addition, the interface valve prevents backflows by working as a non-return valve (Little, 2004). The interface valve is opened by pneumatic controller (Little, 2004; Shammas & Wang, 2010) and it stays open a predetermined time period. One valve cycle is about 6-8 seconds (PDH engineer, 2007).

During one valve cycle, first sewage enters the vacuum sewer line (~2 - 3 seconds) and after that atmospheric air enters the vacuum sewer line (~4 - 5 seconds) (EPA, 1991; PDH engineer, 2007). The movement of the sewage is attributed by the differential air pressure behind and in front of the sewage slug (Water Environment Federation, 2008). In one valve cycle 10 - 50 liters of sewage and 20 - 60 liters of air enter into the vacuum sewer line (Werner et al., 2005). However, the volumes of the air and sewage, and the length of a valve cycle depends on the manufacturer (Shammas & Wang, 2010).

The operation of the pneumatic controller is based on three forces: atmospheric air, vacuum through the vacuum sewer lines and pressure formed by air in the sensor pipe. Rise of sewage level in the collection sump compresses air in the sensor line. The interface valve is opened by this pressure, by spring tension in the valve controller. When the valve is open, the vacuum is taken from the downstream of the valve and applied by the valve controller to the actuator chamber to fully open the interface valve. The interface valve is maintained open a predetermined time period by the valve controller. After the time period has elapsed, atmospheric air is admitted to the actuator chamber to permit spring-assisted closing of the interface valve (DRFN, 2013c; EPA, 1991; PDH engineer, 2007).

2.1.2 Vacuum Sewer Line

The sewage is transported from an individual collection chambers to the vacuum station through a vacuum sewer line by a pressure gradient between the negative pressure in the vacuum sewer line and the positive pressure of atmospheric air at the collection chamber (EPA, 1991; Werner et al., 2005). The main components of the vacuum sewer line (Figure 3) are main line, branch line and service lateral. Main line is a trunk line that enters to the vacuum station and has the largest diameter. Branch line is a smaller diameter line that connects to the main line. Service lateral is typically a 75 mm line that connects the collection chamber to the main line or branch line (PDH engineer, 2007).

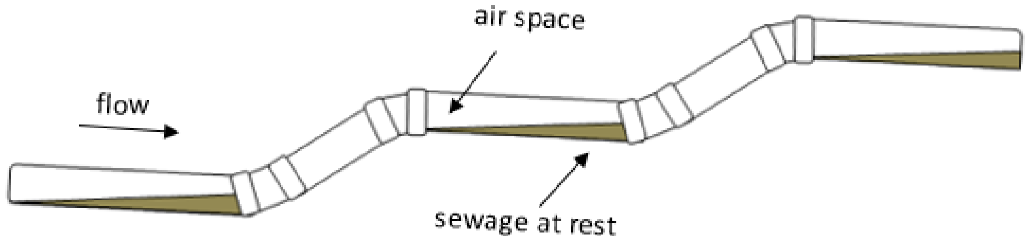

Figure 3. *Saw-tooth profile (modified from Water Environment Federation, 2008).*

Vacuum sewer lines are laid in saw-tooth profile (Figure 3). It means that the sewer line is composed of ”lifts” and positive slopes towards the vacuum station (PDH engineer, 2007). On the positive slopes the sewage is moved by gravity and on the negative slopes the sewage is moved by the differential pressure behind and in front of the sewage slug (EPA, 1991; Werner et al., 2005).

The purpose of the saw-tooth-profile is to keep the trench depth shallow, to transport the sewage uphill and to prevent the pipes from becoming sealed by keeping an open passage way on top of the sewer (PDH engineer, 2007). Air flows above the liquid (Figure 3) and therefore the vacuum can be transferred from vacuum station to each collection chamber of the system. Saw-tooth profile ensures the maximum pressure differential and maximum energy at each collection chamber (PDH engineer, 2007; Shammas & Wang, 2010).

When the sewage enters from the collection chamber to the vacuum sewer line, the sewage travels in the vacuum sewer line as far as its initial energy allows, until the frictional forces causes the stop of the movement (PDH engineer, 2007). The slug of sewage breaks down by pipe friction and allows the air with higher pressure behind the slug slip past. The differential pressure breaks away behind and in front of the sewage slug and the sewage flows to rest at a low point of the profile (EPA, 1991; Shammas & Wang, 2010). At the low point the sewage does not seal the sewer line and air can flow above the liquid, and the vacuum condition is maintained in the entire pipe network (EPA, 1991; Water Environment Federation, 2008).

The atmospheric air also affects the sewage downstream from the operating valve (Shammas & Wang, 2010). After air has slipped past a sewage slug, it continue its move across the next resting sewage slug and makes it move towards the vacuum station until it also breaks down by pipe friction. After number of valve operations the sewage slug reaches the vacuum station (EPA, 1991; Shammas & Wang, 2010). When the interface valves along the sewer line open, each time additional slugs of sewage and air enter the system acting as a subsequent energy inputs. These subsequent energy inputs continue the move of the sewage towards the vacuum station (PDH engineer, 2007).

The pressure differential transports the sewage in the vacuum sewer line at velocity of 4.5 – 5.5 m/s (PDH engineer, 2007). However, the velocity depends on the manufacturer. The sewage transport velocities can vary for example between 3 – 5 m/s (Bilfinger Berger, 2011) or 4 – 6 m/s (Flovac Systems, 2015). The tangential liquid velocity in the vacuum sewer line is above the minimum required for self-cleaning (Water Environment Federation, 2008).

2.1.3 Vacuum Station

From the sewer lines the sewage and air enters to the vacuum station. In the vacuum station the negative pressure is generated and the sewage is collected and pumped to treatment facilities or a conventional sewer system (Corodex Electromechanic, 2008). The main components of the vacuum station are a vacuum tank, vacuum pumps and discharge pumps (Li et al., 2010; PDH engineer, 2007). Other important components located in vacuum station are control panel and stand-by generator (Masteller & Moler, Inc., 2013).

In the vacuum station the sewage first enters to the vacuum tank and accumulates in the bottom part of the tank (Werner et al., 2005). The vacuum tank is provided for the collection of the sewage. It is sealed and vacuum tight vessel (Water Environment Federation, 2008). In addition, the vacuum sewer line and the vacuum pumps are connected on the top part of the vacuum tank. Inside the vacuum tank, the top part is kept open for transferring the -0.68 bar pressure to the sewer lines (PDH engineer, 2007; Water Environment Federation, 2008).

Discharge pumps pump the sewage from the vacuum tank to the treatment facilities or conventional system (Werner et al., 2005). They act in a duty/stand-by mode. It means that they run in cycles, not continuously. When the sewage reaches a certain level in the vacuum tank, a discharge pump turns on and pumps the sewage out of the tank. When the sewage reaches a certain lower level in the vacuum tank, the discharge pump turns off (Li et al., 2010; Werner et al., 2005). The discharge pumps are similar to the pumps that serve gravity sewer system. The only exception is that they must be capable to pump from partial vacuum (Little, 2004).

The negative pressure in the vacuum sewer system is created by vacuum pumps. They also act in a duty/stand-by mode (Little, 2004) and automatic controls are used to operate and alternate the pumps (Schubert et al., 2003). The turn-off level vacuum is -0.68 bars and the turn-on level vacuum is -0.54 bars (Water Environment Federation, 2008).

However, the values of the turn-off level and turn-on level vacuums depend on the manufacturer. The levels can vary for example between -0.55 - -0.65 bars (Li et al., 2010) or -0.5 - -0.7 bars (Flovac Systems, 2015).

To establish the turn-off level vacuum the vacuum pumps run for short period of 3 - 5 minutes. After achieving the turn-off level vacuum they turn off. Slowly the vacuum levels begin to drop due to the interface valves that open and admit atmospheric air to the system. When the pressure in the system reaches the turn-on level vacuum, the vacuum pumps turn on and run until they have re-established the vacuum of turn-off level (PDH engineer, 2007). A central power source is required to operate the vacuum pumps (Masteller & Moler, Inc., 2013; Water Environment Federation, 2008).

Control panel is used to control all of the motor starters, control circuitry, overloads, and the hours-run meters of each discharge and vacuum pump. In addition, vacuum tank level control relays, the vacuum chart recorder and fault monitoring equipment are housed in the control panel (Water Environment Federation, 2008). In the event of power failure the stand-by generator ensures the functioning of the vacuum sewer system and prevents the sewage from overflowing (Little, 2004; Water Environment Federation, 2008).

2.2 Design Considerations

2.2.1 Hydraulics

The sizing of the main components of the vacuum sewer system, including the sizing of the vacuum sewer line and various vacuum station components, is done according to the design flows (Average Daily Flow (Q_{ave}), Peaking Factor (PF) and Peak Flow (Q_{max})). These maximum flowrates are expected to occur once or twice in a day. Instantaneous flowrates are flowrates that can exceed the design flows and they can occur under certain situations (EPA, 1991; PDH engineer, 2007). Vacuum sewer system is a sealed system, therefore groundwater infiltration from the vacuum sewer lines and collection chambers should not happen (PDH engineer, 2007).

Velocity (tangential liquid velocity) of the sewage in the vacuum sewerline needs to be above the minimum required for self-cleaning to prevent blockages (PDH engineer, 2007; Water Environment Federation, 2008). Sufficient velocity for self-cleaning is generally 0.6 – 0.9 m/s (EPA, 1991). The tangential liquid velocity in the vacuum sewer line is above the minimum required for self-cleaning (Water Environment Federation, 2008).

Vacuum transport process is an important feature in the vacuum sewer system. With the saw-tooth profile design concept there is no transport of the sewage when all the interface valves are closed. The remaining sewage rests in the low spots, does not seal the pipe, and minimal vacuum loss is experienced in the system in this condition. An open passage of air is maintained between the interface valves and the vacuum station. This provides maximum differential pressure at the interface valve and ensures maximum energy input to the vacuum sewer line (PDH engineer, 2007).

Vacuum sewer system operates on two-phase (air and liquid) flows and therefore air to liquid (A/L) ratio is an important design factor. Each time an interface valve opens a predetermined volume of air and liquid is admitted to the vacuum sewer lines. There are various attainable A/L ratios for the vacuum sewer system (EPA, 1991; PDH engineer, 2007). However, the recommended minimum A/L- ratio is 2/1 (Water Environment Federation, 2008). Optimum collection sump capacity ensures a constant A/L flow rate (Bilfinger Berger, 2011). In addition, air-intake at gravity line from house to the collection chamber provides a sufficient amount of air to enter the vacuum sewer line. The A/L ratio can be adjusted also by adjusting the interface valve controller timing (PDH engineer, 2007).

The vacuum levels in the vacuum sewer line drop when an interface valve is open, due to the energy loss caused by admitting sewage into the vacuum sewer line. The drop of vacuum levels decreases the valve capacity. The lower pressure differential results in decrease of available energy and in slower sump evacuation time. Vacuum recovery is a property of the vacuum sewer line that takes place when the valve is closed. It recovers the vacuum levels in the sewer line to the same level that existed before the valve opened. It is a function of the pipe diameter, line length, number of connections and the amount of the lift in the system (EPA, 1991; PDH engineer, 2007).

Inadequate vacuum levels in the system cause lower pressure differential and lower amount of available energy and therefore the valve capacity and the A/L ratio decrease as well. Many small energy inputs (collection chambers) located constantly along the sewer line is the best option to keep the appropriated vacuum levels, whereas the worst option is to have a large flow input located at the utmost end of the sewer line (PDH engineer, 2007).

Static and friction losses are also important design parameters of the vacuum sewer system. The minimum vacuum of the system (-54 bars) results in total head loss of 5.5 m. Operation of vacuum valves requires 1.5 m of the head loss and after that 4.0 m is available for sewage transport. Therefore the summation of static loss and friction loss should not exceed 4.0 m (EPA, 1991; PDH engineer, 2007). Static losses are caused by the lifts of saw-tooth profile or by vertical profile changes. The smallest possible profile changes ensure the most efficient use of available energy. In addition, several lifts are more recommended than one large lift. Friction losses are ignored in slopes greater than 2.0 % (EPA, 1991; PDH engineer, 2007).

2.2.2 Odors, Noise and Corrosion

In the vacuum sewer system the vacuum station is the component that typically might cause noise or odor nuisance (Buchanan et al., 2010). The vacuum stations concentrates the withdrawal of air from the vacuum sewer system in one spot (Paulette, 2006) and the vacuum pump exhaust contains H_2S. In the other components of the system the nuisance caused by odors are significantly reduced because vacuum sewer system is a sealed system from the collection chambers to the vacuum station. In addition, large amount of air is introduced at each collection chamber and the system has short detention times (Buchanan et al., 2010; PDH engineer, 2007).

Noise is typically generated by the vacuum pumps in the vacuum station. Noise nuisance can be decreased by installing soundproofing features to the vacuum station (PDH engineer, 2007). The odors at the vacuum station can be eliminated by using biomass compost bed, chemical neutralization, activated carbon absorption systems or absorption by manufactured biomass filters (Buchanan et al., 2010; PDH engineer, 2007).

Nine vacuum sewer systems have been installed and various odor control methods were constructed and modified at the vacuum sewer systems in the City of Albuquerque by the year 2006. The standard method for each new vacuum station became the biofilters using city sludge compost. The components of the biofilter were concrete construction, corrosion resistant coating and open side to maintain and replace the compost material at regular intervals. H_2S removal rates of 95 – 100 % have been observed. However, the airflow rate discharged from the vacuum pumps can be highly variable and at times the airflow rate have exceeded the capacity of the biofilters. In addition, if the system is depressurized during the maintenance, initial vacuum pump flow rates have been higher than the biofilters were designed to receive (Paulette, 2006).

The daily sewage flows of the vacuum sewer system might be lower than the flows of the gravity sewer system. It is due to a fact that the vacuum sewer system requires less water to operate as gravity sewer system, and vacuum sewer system can serve households that consume less water. In addition, for the same reason the concentration of wastewater from the vacuum sewer system might be higher (Little, 2004). To avoid corrosion materials that are resistant to corrosion should be used for all the parts of the system that are in contact with sewage (EPA, 1991; PDH engineer, 2007).

2.2.3 Collection Chambers

Collection chamber size and layout vary depending on the manufacturer. The material of collection chamber body is usually polyethylene (PE) (Bilfinger Berger, 2011) or fiberglass (EPA, 1991; PDH engineer, 2007). All the joints and connections must be water-tight to avoid groundwater infiltration (PDH engineer, 2007). In addition, surface water should not enter the collection chamber (Fábry, 2015). If the capacity of collection chamber is not sufficient in the high flow areas, a buffer tank with bigger capacity can be installed (PDH engineer, 2007).

Collection sump size is 25 % of average daily flow in order to prevent flooding during an event of breakdown (Fábry, 2015; Little, 2004). Recommended maximum peak flow rate for collection chamber is 0.03 – 0.09 l/s and recommended minimum sump volume is 190 l (Water Environment Federation, 2008). The sumps must be watertight, made of corrosion resistant material and designed to be durable against the forces exerted on them. Additional venting should be provided without nuisance (Little, 2004).

Interface valve located in the collection chamber is typically either a piston-type or diaphragm-type valve (PDH engineer, 2007). Interface valve should be capable to operate submerged (Little, 2004) and it should be made of materials that are chemical resistant to gases and sewage constituents (PDH engineer, 2007). Each time when an interface valve is open, full amount of water should be able to pass the valve, and the valve should not obstruct the water flow from the sump (Little, 2004).

Maximum peak flow for an interface valve is 0.2 l/s for the 75 mm valve and 0.13 l/s for the 65mm valve (Bilfinger Berger, 2011). However, the recommended minimum valve size is 75 mm (PDH engineer, 2007; Water Environment Federation, 2008). Pressure differential between the atmosphere and vacuum exists in the system when the valve opens. Energy loss through the interface valves can be minimized by using the interface valve with a high Flow Coefficient (C_v) factor. C_v factor is the flow rate in liters per minute (PDH engineer, 2007).

Valve controller needs a source of atmospheric air to the actuator chamber to ensure that the interface valve is being closed at the end of each valve cycle. Without air the valve would stay in the open position. Breather is a component that provides the air to the actuator chamber. There are two types of breathers: external and in-sump breathers. In the case of external breather the entire piping system must be watertight and there must be a slope towards the collection chamber. If the maintenance or installation of breathers is not done properly the result might be water directly pulled in the controller and failing of the interface valve (continuously in open position). The in-sump breather uses atmospheric air from the sump to close the valve controller. In case of a low vacuum condition, the in-sump breather protects the controller from unwanted liquid (PDH engineer, 2007).

The collection chambers works as ”energy inputs” of the vacuum sewer system, therefore the locations of the collection chambers is also an important design consideration. Long distances without collection chambers should be avoided. Collection chambers should be located regularly along the sewer line (PDH engineer, 2007). The installation depth of the collection chamber depends on the house connection. House connections from houses to the collection chambers are gravity lines and they should be laid at slope of 1:60 or steeper and the minimum pipe size of house connection is 100 mm (EPA, 1991; Little, 2004). The pipe size of the gravity line depends on the amount of flow and local requirements. The house connection pipe material is Polyvinyl Chloride (PVC) and 1- 4 houses can be connected to one collection sump (PDH engineer, 2007). Each house connected to the vacuum sewer system should have an own house connection (Masteller & Moler, Inc., 2013). Backflow into the houses should be prevented (EPA, 1991; Little, 2004).

Cycle counter counts the valve cycles for three possible reasons: to determine if the valve is capable for keeping up with the flow (typically located to place where large water use is expected or excessive amount of infiltration in the building sewer is suspected), to estimate the amount of sewage or amount of extraneous water entering the system (PDH engineer, 2007). Electronic Air Admission Control (EAAC) is used in case the vacuum falls below the pre-set limit in the vacuum sewers. EAAC monitors the vacuum level and incase of low vacuum it opens and admits atmospheric air to the system to boost sewage through the lifts towards the vacuum station. Typically EAAC is not part of the design, it is added to already operating system to improve the liquid transport (PDH engineer, 2007).

2.2.4 Vacuum Sewer Line

The main items to take into account during the design phase of vacuum sewer line are multiplying the service zones, minimizing the pipe sizes and minimizing the static loss. The vacuum sewer system plans should present the profiles of the vacuum sewer lines. The profiles should include line sizes and lengths, slopes, utility crossings, inverts and surface replacements (EPA, 1991; PDH engineer, 2007). Vacuum sewer system is normally designed to be branched (Bilfinger Berger, 2011; PDH engineer, 2007). The piping profiles vary depending on the manufacturer.

The pipe material for the vacuum sewers (main lines, branch lines and service lateral) is typically PVC (Bilfinger Berger, 2011; EPA, 1991; Masteller & Moler, Inc., 2013) or PE (Bilfinger Berger, 2011; Sekisui Chemical, 2015). Joints are commonly O-ring rubber gasketed pipes for PVC piping (Water Environment Federation, 2008) and electro fusion welded for High Density Polyethylene (HDPE) piping (Bilfinger Berger, 2011). The pipes and joints must be certified for use under vacuum condition. Suitable pressure rating for the vacuum sewer is 9 bars (Little, 2004). Standard Dimension Ratio (SDR) 21 is suitable for PVC pipes and SDR 11 for HDPE pipes with pipe sizes of 90 - 250 mm (Bilfinger Berger, 2011). Expansion and contraction induces stress, therefore flexible elastomeric joint pipe is recommendable. In addition, routing horizontally around obstacles is possible with flexible small diameter PVC-pipe (PDH engineer, 2007).

The pipe size depends on the design flows and the amount of the houses connected to the vacuum sewer line (Table 1). The more houses connected to the sewer line the bigger pipe diameter is needed (PDH engineer, 2007). The recommended minimum pipe diameter is 100 mm for the mainlines (Water Environment Federation, 2008).

Table 1. *Relation between the vacuum pipe diameters, maximum number of houses connected to the network and maximum flow for the pipe size. Peak Flow = 0,032 l/s/house (Water Environment Federation, 2008).*

Pipe Diameter (mm)	Maximum Number of Houses Connected	Maximum Flow for the Pipe Size (l/s)
100	80	3,5
150	210	9,5
200	420	19,2
250	750	34,4

The size of the interface valve also affects on the pipe size. The interface valve size should always be smaller than the pipe size downstream of the valve. However, the minimum interface valve and service lateral size should be Diameter Nominal (DN) 75 and the minimum size of the vacuum sewer should be DN 90 (Little, 2004). Pipe sizes can be minimized by dividing the area into multiple service zones and by spreading the peak flow among the various zones (PDH engineer, 2007).

Multiple service zones means that the vacuum station is located centrally and has multiple vacuum sewer lines entering the station that divides the service area into zones (Buchanan et al., 2010; PDH engineer, 2007). The advantages of having multiple service zones is the service reliability and operational flexibility. In case of a system failure the problem zone can be tracked and isolated from the rest of the system (PDH engineer, 2007).

Division valves are used to isolate different services zones. Typical division valves are located at the intersections of branch lines and main lines, at both sides of a bridge crossing and at both sides of areas of unstable soil. In addition, on long routes they are located in intervals of 450 - 600 m (PDH engineer, 2007; Shammas & Wang, 2010). The requirements for the division valves is a capability to sustain a vacuum of -0.80 bar. The division valve type is usually a gate valve (PDH engineer, 2007; Water Environment Federation, 2008).

The laying depth of pipes depends on the climate conditions. Typically the vacuum pipes are laid in depth of 90 cm and in cold regions (northern United States) the depth is 120 - 150 cm (EPA, 1991; Paulette, 2006). In cold regions, besides of the depth of the trench, the short retention time in small diameter lines and inherent turbulence avoid the line from freezing. Deep trenches are avoided in vacuum sewer system by using pressure difference to transport the sewage (EPA, 1991; PDH engineer, 2007).

The length of the vacuum sewer line is governed by the static and friction losses. The topography, sewage flows and pipe diameter affect on the maximum line length (from vacuum station to line extremity) (EPA, 1991; PDH engineer, 2007; Sekisui Chemical, 2015). Static loss can be minimized by adjusting ideally the items that result in static loss. These items are elevation, line length, utility conflicts and the relationship of the collection chamber location to the vacuum sewer line (PDH engineer, 2007).

Usually with positive elevation the line is longer and with negative elevation the line is shorter. Utilities are recommended to cross over instead of crossing under to minimize the lift caused by utility conflicts. In addition, locating the vacuum station centrally the length of longest line and vacuum loss caused by lifts is minimized (PDH engineer, 2007). Typical length for a vacuum sewer system is 2 - 4 km. However, even extension to length of 5 km can be possible (Sekisui Chemical, 2015).

The pipes are recommended to be laid in saw-tooth profile with many small lifts instead of one big lift (Little, 2004). The slope of the pipes should adapt to the slope of the ground (Bilfinger Berger, 2011; Shammas & Wang, 2010). However, the minimum slope of the pipes should be 0.2 % (EPA, 1991; Flovac Systems, 2015; Little, 2004; Shammas & Wang, 2010). Minimum distance between lifts is 6 m and a single lift should not exceed 0.9 m (EPA, 1991; Water Environment Federation, 2008).

2.2.5 Vacuum Station

The design considerations of vacuum station vary depending on the manufacturer. Important design parameters for the vacuum station are station Peak Flow ($Q_{max,}$ l/min), Station Average Flow ($Q_{a,}$ l/min), Station Minimum Flow ($Q_{min,}$ l/min), Discharge Pump Capacity ($Q_{dp,}$ l/min), Vacuum Pump Capacity ($Q_{vp,}$ m3/h), Vacuum Tank Operating Volume (V_o, l), Vacuum Tank Volume (V_{vt}, l), Reservoir Tank Volume (V_{rt}, l), System Pump-Down Time (t, min), Piping System Volume (V_p, l), Total System Volume (V_t, l), Total Dynamic Head (TDH, m), Static Head (H_s, m), Friction Head (H_f, m) and Vacuum Head (H_v, m) (EPA, 1991).

The vacuum station is typically located as centrally as possible (EPA, 1991; Paulette, 2006) and the service area of vacuum sewer system should have at least 150 users (Masteller & Moler, Inc., 2013). Vacuum station is typically a two floor concrete building (EPA, 1991; Shammas & Wang, 2010). Vacuum pumps are located upstairs and vacuum tank and discharge pumps downstairs. The vacuum tank is located in vacuum station at lower elevation than most of the components. This arrangement ensures that there is a minimum lift required when wastewater enters the vacuum tank from the top part of the tank (Water Environment Federation, 2008).

The minimum amount of vacuum pumps is two (EPA, 1991) and the type of the vacuum pumps is typically sliding-vane, but also liquid-ring type is used (PDH engineer, 2007; Shammas & Wang, 2010; Water Environment Federation, 2008). When the system has two pumps, each pump should be able to provide 100 % design capacity (EPA, 1991;

PDH engineer, 2007). When the system has 3 - 5 vacuum pumps, the design capacity should be met with one pump out of service (PDH engineer, 2007).

Vacuum pumps are typically sized to operate 3 - 5 h/d (Shammas & Wang, 2010). According to another opinion, the vacuum pumps are sized to operate 30 % of the time (7.2 h/d) (Little, 2004). Vacuum pumps should be capable to operate continuously as well as operate minimum of 12 starts per hour and the maximum recovery time should be 30 minutes in case of a power failure, system breakdown or intentional switch off (Little, 2004). During the troubleshooting and emergency the pumps might need to be able to provide a vacuum of 0.84 bars. The minimum recommended vacuum pump size is 4.3 m^3/min (Water Environment Federation, 2008).

The sizing of the vacuum pumps is based on peak flow, length of the line and total system piping volume. Initial sizing of the vacuum pumps (Qvp) depends on the Peak Flow (Q_{max}) and the length of the line. After the initial sizing of the vacuum pumps, a second calculation is made to ensure that the capacity of the vacuum pumps is large enough for the pipe volume connected to the system. It is ensured by calculating the evacuation time of the vacuum sewers in a vacuum of -0.54 – -0.68 bars for the selected vacuum pumps (PDH engineer, 2007). The system pump down time should be 1 - 3 minutes (Water Environment Federation, 2008).

In the vacuum it is recommended to have only one vacuum tank. Only rarely when the single tank is too large to transport, dual tanks are recommended (PDH engineer, 2007). However, the maintenance would be easier if the amount of the vacuum tanks is more than one. When one tank is under maintenance there would at least one tank operating (Little, 2004).

The material of the vacuum tank is either carbon steel, stainless steel or fiberglass (Shammas & Wang, 2010; Water Environment Federation, 2008). In addition, vacuum tank should have required number and size of openings, taps and man-ways (EPA, 1991; Little, 2004; PDH engineer, 2007) to provide an access for cleaning and for internal inspection. In addition, a level control system is located in the tank. The control system should be suitable for the conditions under which the tank is operating (Little, 2004). The working pressure of the vacuum tank is -0.68 bars and the testing pressure of the tank is -0.95 bars (PDH engineer, 2007).

There are three factors that are taken into account when sizing the vacuum tank: the peak flow to the vacuum station, adequate operation volume (to prevent discharge pumps from operating in shorts cycles) and emergency storage volume (PDH engineer, 2007). The operation volume of vacuum tank is equal to the sewage accumulation required to restart the discharge pump (Shammas & Wang, 2010). The maximum operation time for the discharge pumps should be four times per hour at minimum flow periods and seven times per hour at average flow period (EPA, 1991; PDH engineer, 2007; Shammas & Wang, 2010).

Emergency volume is calculated by applying a safety factor of 3.0 to operating volume (V_o) of the vacuum tank. The total volume of the vacuum tank (V_{vt}) is calculated by applying an additional 1.5 m^3 as a reserve volume within the tank, for vacuum pump reserve volume and for moisture separation (PDH engineer, 2007; Shammas & Wang, 2010). The recommendation for the minimum size of vacuum tank is 3.8 m^3 (PDH engineer, 2007). According to another opinion, the size of small collection tank is 1.23 m^3 and the size of large collection tank is 18 m^3 (Sekisui Chemical, 2015).

The type of the discharge pumps is usually either dry well or wet well, because these types are easier to maintain than submersible pumps (Little, 2004). In addition, the pumps are usually horizontal, non-clog centrifugal pumps, because the suction losses are lower compared to the vertical pumps (EPA, 1991; PDH engineer, 2007). Recommended materials for the discharge pumps are cast iron with stainless-steel shafts and avoided materials are cast aluminum, bronze and brass (EPA, 1991; Water Environment Federation, 2008).

The minimum amount of discharge pumps is two. Each pump should be capable to provide 100 % of the design capacity (EPA, 1991), passing 100 mm solid and operate under negative pressure without cavitation (Little, 2004). In addition, the pumps must be capable to start 12 times in an hour (Little, 2004). To prevent pumps from starting excessively and from increased wear, a minimum pump running time (recommended 2 minutes) can be set by the level controls (Water Environment Federation, 2008).

The liquid should have equal level on both sides of the discharge pump impellers to remove air and to allow the pumps to start without having to pump against the vacuum in the vacuum tank. Equalizing lines ensure the equal liquid level (EPA, 1991; Water Environment Federation, 2008). Recommended material for the equalizing line is clear PVC to observe air leaks and blockages (PDH engineer, 2007).

The sizing of the discharge pumps is based on total peak flow (Q_{max}) to the vacuum station (PDH engineer, 2007) and discharge pump capacity (Q_{dp}), Total Dynamic Head (TDH) and Net Positive Suction Head (NPSH) are calculated for the discharge pumps. Q_{dp} depends on the Q_{max} and it should be 20 % greater than the Q_{max} for each pump (Shammas & Wang, 2010). TDH is a summary of static head (H_s), friction head (H_f) and vacuum head (H_v) (PDH engineer, 2007). The additional H_v is required to pump against the vacuum in the vacuum tank (Shammas & Wang, 2010). Typically the value of H_v is 7 m, which is equivalent to the operating value of -0.68 bars. Pumps with a flat capacity-head curve should be avoided (PDH engineer, 2007).

NPSH need to be sufficient to overcome the vacuum of the vacuum tank (Shammas & Wang, 2010). The location of the discharge pumps is usually below the vacuum tank to minimize NPSH (EPA, 1991; Water Environment Federation, 2008). The discharge pump suction lines should be placed at the lowest point on the tank and at the farthest point from the vacuum sewer line inlets (PDH engineer, 2007).

Stand-by generator should provide 100 % stand-by power for the operation of the vacuum sewer system in the case of power failure (PDH engineer, 2007; Shammas & Wang, 2010). The stand-by generator should start automatically in the event of a power failure (Little, 2004). Control panels are usually specially designed for each vacuum station and attached directly to the equipment skid. The control panel includes starter for each motor, discharge pump level control relays, hour-run meters of the pumps and alarm dialer to monitor alarms. Monitoring system uses telemetry equipment. It alerts the operator regarding irregularities, such as low vacuum level, high sewage conditions and power failure (PDH engineer, 2007; Shammas & Wang, 2010).

2.3 Operation and Maintenance

To function successfully the vacuum sewer system must have at least one operator that is responsible for the entire system. The system operator should be trained for the operation and maintenance of the system and be familiar with the system, including the locations of all the collection chambers, lines, division valves and other key components. The operator must understand how the main components of the vacuum sewer system are interrelated and work together as a system (Water Environment Federation, 2008).

Maintenance of the vacuum sewer system can be divided into two groups: normal and preventative maintenance, and emergency maintenance. Concentrating on the normal and preventative maintenance minimizes the need of emergency maintenance (Water Environment Federation, 2008). Maintenance of the vacuum sewer system is done by regular inspection of system components by staff or remote monitoring by telemetry (Buchanan et al., 2010). The vacuum sewer system has recommended maintenance tasks and in case of a failure there is a troubleshooting method to track the failure (Bilfinger Berger, 2011). The design, construction and operation of the system affects to the maintenance. They must follow the instruction of the licensor to operate the system easily (Fábry, 2015).

2.3.1 Normal and Preventative Maintenance

According to the manufacturers' recommendations, normal and preventative maintenance should be done daily, and the maintenance should be planned and scheduled. The plans and schedules include information regarding time, personnel and equipment. In addition, costs, work orders and priorities are included to the plans (EPA, 1991; Water Environment Federation, 2008). The normal and preventative maintenance task can be divided into daily, weekly, monthly, every 6 months and annual tasks. Table 2 presents the recommended maintenance tasks of vacuum sewer system of Roediger Vacuum

(Bilfinger Berger, 2011). However, the tasks vary depending on the manufacturers' recommendations.

Table 2. *Maintenance schedule of vacuum sewer system provided by Roediger Vacuum (Bilfinger Berger, 2011).*

	Maintenance Tasks
Daily	
	Change recorder chart (vacuum level) Record pump run times (vacuum and discharge pumps) Check oil level in vacuum pumps Visually check discharge pumps (leakage, flow rate) Visually check pressure equalization lines (flow-blockages) Check control panel lights Check alarm dialer function Fill out daily equipment check-up log book
Weekly	
	Check alarm points and proper system function. Run simulation program Visually/audibly check vacuum station operation. Check vacuum pump oil (discoloration, moisture) Check vacuum pump exhaust filter gauge Manually operate valves in equalization lines
Monthly	
	Manually operate plug valves of incoming vacuum lines Manually operate plug valves of sewage pump suction and discharge lines Clean Vacuum Tank sight glass (if required) Clean equalization lines (if required) Check liquid level sensor signal (compare with sewage level in sight glass) Check vacuum sensor (absolute pressure) (compare with vacuum tank gauge or test gauge (differential pressure)) Check pressure sensor or force main, if used (compare with pressure gauge on force main) Check sump for proper valve cycling Check biofilter (flow distribution, settling of biomaterial)
Every 6 months	
	Check pump motors and couplings (wear, deterioration, misalignment, overheating) Check alarm signals of the vacuum pumps
Yearly	
	Open vacuum tank, clean out deposits (if required) and inspect coating Replace vacuum pump exhaust filter (if required) Replace air inlet filter (if used) Clean liquid level sensor (wipe-off) Check control panel for dirt, moisture, check for loose writing, etc. Vacuum pumps: every 1000 hours or annually replace oil (in case of oil-cooled pump) and oil filters and reset timers. First replacement of oil after 500 hours. Floating switch cleaning and testing

Normally the vacuum station is visited daily to record the pump running hours, to check the oil levels and to check visually the vacuum station operation. The daily visit takes about 30 minutes (Buchanan et al., 2010; EPA, 1991; Water Environment Federation, 2008). By following the daily values, the operator can notice from the beginning any emerging deficiencies caused for technical reasons (Fábry, 2015).

The collection system (vacuum sewer line and collection chambers) is visited rarely. Only areas with difficult or unusual conditions are visited periodically. The collection system is mainly monitored by reading charts (EPA, 1991; Water Environment Federation, 2008). The vacuum chart recorder enables the operator to recognize any valve block due to foreign objects (Fábry, G, 2015).

Division valves should be checked at least twice a year to keep the valves in operation conditions (EPA, 1991; Water Environment Federation, 2008). Once a year all the interface valves should be inspected, and every ten years all the interface valves should be changed to new ones. The seals and the diaphragms of the valve controllers should be replaced every five years (EPA, 1991; Water Environment Federation, 2008). The controllers should be replaced every ten years. In addition, vacuum tanks should be cleaned every year (Bilfinger Berger, 2011). Tasks of preventative maintenance include annual visual inspections of collection chambers and valves, rebuilding controllers every 3 to 6 years and valve every 8 to 12 years (Buchanan et al., 2010).

Maintenance of the discharge pumps include checking that there are no blockages and that the impeller rotates easily. In addition, water should not be present in the oil reservoir of the pump. There are trouble-shooting mechanisms for the discharge pumps in case of failure. Trouble-shooting is convenient when the pump does not convey any wastewater, there is air in the pump housing or the pump motor does not run (Bilfinger Berger, 2011).

2.3.2 Emergency Maintenance and Alarms

Emergency maintenance takes places in case of a malfunction of the system. The malfunction might occur in the vacuum sewer line, collection chamber or vacuum station. Normally more than one person is needed to carry out the emergency maintenance. The emergency maintenance might occur after normal working hours (EPA, 1991; Water Environment Federation, 2008). The maintenance calls take place 4 to 5 times per month and most of them are minor adjustments to the automatic opening settings for the vacuum valve in the vacuum sewer systems of the City of Albuquerque (Paulette, 2006).

In most of the cases the emergency maintenance is related to the interface valves. They are either stuck in open or closed position. The cause is usually low vacuum or extraneous water in the controller. A valve stuck in closed position causes failures with toilet flushing or backup the wastewater to the property. An open valve causes vacuum loss in the vacuum sewer line. The malfunctioning interface valve can be located by following operating instructions (Buchanan et al., 2010; EPA, 1991; Water Environment Federation, 2008).

Malfunctioning in the vacuum sewer line is normally caused by a line break, for example due to excavation for other utilities. Line break causes vacuum loss. The problem zone can be isolated by using division valves (EPA, 1991; Water Environment Federation, 2008). Malfunctioning in the vacuum station is normally caused by a pump, motor or electrical control breakdown (EPA, 1991).

Vacuum station should be equipped with a fault monitoring system. The system monitors the vacuum station and the collection system. The system also notifies automatically the operator in case of low vacuum, high levels of wastewater in collection tank and power failures (EPA, 1991; Water Environment Federation, 2008). High level alarm, low vacuum alarm and vacuum pump excessive run time alarm have troubleshooting methods. (Bilfinger Berger, 2011)

High liquid level alarm indicates that the sewage has reached the maximum level in the vacuum tank. A possible cause can be a discharge pump failure, clogged discharge pump suction or discharge line, a sensor failure or excessive sewage flow. Low vacuum alarm indicates a loss of vacuum in the vacuum sewer line. A possible cause can be a failure of a vacuum pump, vacuum sensor failure, an open interface valve (stuck) or a leak in the vacuum sewer line (damaged pipe or a missing cap of inspection pipe). Vacuum sewer line leaks can be spotted with a ball test. Vacuum pump excessive run time alarm indicates that all the vacuum pumps run continuously. A possible cause for the alarm can be a leak in the vacuum sewer line that avoids the pumps to reach the shut-off point, vacuum sensor failure, or wear or plugged biofilter that lowers the vacuum pump capacity (Bilfinger Berger, 2011).

2.3.3 Spare Parts, Maintenance Tools and Documentation

To optimize the operation efficiency, there should always be spare parts in stock. Some of the spare parts of the vacuum sewer system are unique and therefore it might be difficult to purchase them locally. However, some of the spare parts such as fittings and pipes can be purchased locally (Water Environment Federation, 2008). Also specific maintenance tools and equipment are required for the maintenance of the vacuum sewer system. This kind of specific tools are for example sensor pipe puller, valve repair stand, vacuum gauges and controller test box (Water Environment Federation, 2008).

Essential documents for the maintenance of the vacuum sewer system are record keeping and as-built drawings. Record keeping is important for the efficient operation of the system. The first step of troubleshooting is analysis of the records. The records can be divided into four groups: normal maintenance records, preventative maintenance records, emergency maintenance records and operating costs records (EPA, 1991).

As-built drawings are essential tools for the operation and maintenance, for troubleshooting and for future improvements. During the construction phase of the vacuum sewer system is commonly done changes. The changes should be marked on the as-built drawings. The drawings should depict exactly how the system was built. In the as-built drawing should be marked all the key components of the system. In addition, line sizes, line identifications, collection chamber numbering and locations, and division valve locations. As-built hydraulic map should include information regarding the locations of every lift, the amount of vacuum loss at the key locations, number of branches, number of valves in each branch, and total volume of pipe in each branch (EPA, 1991).

2.3.4 Operator Survey

A vacuum sewer system company (AIRVAC) prepared an internal survey regarding operation and maintenance of the vacuum sewer systems in 2003. A survey form was sent to selected operators of vacuum sewer systems. Operation and maintenance data was gathered from 22 projects, with a total of 49 operating systems. It represented 20 % of the operating systems in the United States. Table 3 presents data regarding vacuum sewer system maintenance times (hours/year/component) (Water Environment Federation, 2008).

Table 3. *Reported maintenance time range in vacuum station (hours/year/component).*

Category	Low	High	Average
Vacuum Station			
Routine	100	600	250
Preventative	0	90	50
Emergency	0	85	30
Vacuum Mains			
Routine	0	100	30
Preventative	0	100	20
Emergency	0	110	10
Interface Valves			
Routine	0,2	0,9	0,5
Preventative	0,0	1,0	0,4
Emergency	0,1	1,35	0,6

The maintenance effort was break into 3 categories: routine, preventative and emergency. Routine means day to day maintenance, preventative means planned and scheduled maintenance and emergency means service calls (Water Environment Federation, 2008).

2.4 Areas of Application

Vacuum sewer system is practical when the local topography is flat and the ground is thaw unstable, according to the vacuum sewer system companies. In flat area the gravity sewer system needs many pumping stations to avoid deep trenches. In the areas with rock close to the ground surface, high water table and running sand it is difficult to dig deep trenches for gravity sewer system (Elawwad et al., 2014). Table 4 presents applicable areas of vacuum sewer system.

Table 4. *Applicable areas of vacuum sewer system. [1] EPA, 1991 [2] Jones et al., 2001[3] Królikowska et al., 2013 [4] Little, 2004 [5] Miszta-Kruk, 2015 [6] Water Environment Federation, 2008 [7] Buchanan et al., 2010. ND=no data.*

Feature	Area of Application
Saw-Tooth Profile & Shallow Trenches	Relatively flat ground, uphill, unstable soil and areas where rock, running sand or water table is near the ground surface. [1-5]
Small Pipe Diameter & Shallow Trenches	Restricted construction conditions, existing urban development where other utilities exist and new and dense urban areas with narrow streets. [1,6,7]
Smaller Water Demand	Countries with poor water resources. [1,4]
Sealed System	Areas with sensitive ecosystems. [6,7]
ND	Smaller communities and rural areas where the population density is low and yard taps. [1,4,7]

Vacuum sewer system has a limited capability to transport sewerage to uphill (4.5 - 6 m) and therefore it is more recommended for flat or gently rolling ground. Ideal location for vacuum sewer system is an area with much natural slope (Buchanan et al., 2010; Jones et al., 2001; Water Environment Federation, 2008).

In the areas where the system is not well known (for example in Africa) the design and installation do not reach the standards (Little, 2004). The system is said to be more suitable for wealthy areas where good solid waste disposal services are provided and soft biodegradable anal cleansers such as toilet paper are used. In informal settlements these are not provided or used (Taing et al., 2011).

Vacuum sewer system can be used also in ships and airplanes (Miszta-Kruk, 2015; PDH engineer, 2007) and in places with intermittently sewage generation (camping sites and holiday centers). In addition, it can be installed in underground railway tunnels, large industrial halls and construction sites (Miszta-Kruk, 2015). Black and grey water separation is also possible with vacuum sewer system technology. Vacuum toilets can be used for black water collection and pneumatic interface valves for greywater collection (Shammas & Wang, 2010).

2.5 Benefits and Challenges

Vacuum sewer system has different features than gravity sewer system and some of the different features has benefits (Table 5). These features are for example saw-tooth profile, shallower trenching, vacuum conditions and high scouring velocities.

Table 5. *Benefits of vacuum sewer system. [1]EPA, 1991 [2] Li et al., 2010 [3] Taing et al., 2011 [4] Schubert et al., 2003 [5] Masteller & Moler, Inc., 2013 [6] Beauclair, 2010.*

Feature	Benefit
Saw-Tooth Profile [1]	Field changes easy to make [1] Ability to avoid unexpected obstacles [1]
Shallower Trenching [1,2,3,6]	Reduce excavation costs [1-3] Reduce environmental impacts [1-3] No need for heavy machinery [6] Local labor can be used [6]
Vacuum Conditions in the Sewers [4]	Less leakages and contamination [4] Reduction in water use [1,4] Less pumping stations [2,3] Smaller pipe sizes [1] Shallower trenching [1-3] High scouring velocities [1]
High Scouring Velocities [1]	Less blockages [1]
Sealed Pipe Joints [5]	Less infiltration [5]
ND	No manholes [1] One power source [1] Less residential relocation [2,3]

The weaknesses of the vacuum sewer system can be divided into three areas: system design, component reliability, and lack of operation and maintenance guidance (EPA, 1991). The present challenges with the vacuum sewer system components were listen in 2008. They were pump cavitation, wastewater into vacuum pumps, line breaks, broken fitting, equipment malfunction, faulty level control, system waterlogging, water in controller, infiltration and inflow. Most of the challenges occurred rarely. The most common failure was water in controller that occurs as a direct result of extraneous water that is allowed to enter the system (Water Environment Federation, 2008). Table 6 presents the challenges of vacuum sewer system.

Table 6. *The challenges with vacuum sewer system. [1] PDH engineer, 2007 [2] Masteller & Moler, Inc., 2013 [3] Little, 2004.*

Component/ Feature	**Challenge**
Interface Valve [1]	Fail in the open position Fail in the closed position [1]
Vacuum Sewers [1]	Broken or leaking sewers [1]
House Connection [1]	Leaking sewers [1]
External Breather [1]	Water entering the controller [1]
Power Failure [2]	Overflowing of sewage [2]
Design and Installation [3]	Do not reach standard in the areas where the technology is not well known [3]
Maintenance [3]	Lack of skills in rural communities [3]

Insufficient vacuum commonly cause interface valves to fail in closed position, less commonly the cause is physical defect. Another cause for interface valve failures is extraneous water in the controller. A valve stuck in closed position causes failures with toilet flushing or backup the wastewater to the property. An open valve causes vacuum loss in the vacuum sewer line (Buchanan et al., 2010; EPA, 1991; Water Environment Federation, 2008).

Vandalism is typical cause of failures with external breathers. The external breather have been consistently the largest cause of valve failures due to water entering the controller. Because of this, in-sump breathers is more common in recent systems. In-sump breather uses atmospheric air from the sump to close the valve controller. In the event of low vacuum conditions where the valve would not open, floats in the in-sump breather protects the controller from unwanted liquid (PDH engineer, 2007).

Malfunctioning in the vacuum sewer line is normally caused by a line break, for example due to excavation for other utilities. Line break causes vacuum loss. The problem zone can be isolated by using division valves (EPA, 1991; Water Environment Federation, 2008). Malfunctioning in the vacuum station is normally caused by a pump, motor or electrical control breakdown (EPA, 1991).

The impact of broken vacuum sewers is low vacuum conditions in the sewers and the sewage may backflow into the house. Backflow protection can be provided by backwater valves on the house connection sewers. With house connections the common challenges are infiltration via leaking sewers (PDH engineer, 2007). Typical challenge during a power failure can be overflowing of sewage. However, the problem can be avoided by using a stand-by generator (Masteller & Moler, Inc., 2013).

Operation and maintenance of vacuum sewer system might be challenging in remote and developing areas (Elawwad et al., 2014). Skills to maintain a vacuum sewer system are not always available in rural communities (Little, 2004). Vacuum sewer system has a relatively complex control and pumps, therefore qualified and trained operators are required (Schubert et al., 2003).

One of the challenges with vacuum sewer system in developing regions is how to help the communities in management of the system. For example, vacuum sewer system is unknown among the sewerage practioners in Egypt, therefore the maintenance of the system is challenging. The result might be that contract specifications might not be up to standards and inferior installations are constructed. A solution could be outsourcing of operation and maintenance in remote areas. Other option is social mobilization to help the households to manage the system by themselves. In the case households manage the system, training must be provided and regular visits must be done by the responsible authority (Elawwad et al., 2014).

2.6 Costs

The installation costs of vacuum sewers are site-specific and therefore the costs vary significantly from case to case. Examples of the factors that affect on the construction costs are geographic area, time of year, local climate and local economics. The geographic area include factors such as rock near the ground surface, unstable soil and groundwater (Buchanan et al., 2010; Shammas & Wang, 2010; Water Environment Federation, 2008).

Cost-effectiveness of the vacuum sewer system depend on the number of connections per vacuum station. Information regarding minimum amount of customers per vacuum station for the vacuum sewer system to be cost-effective vary between 75 – 100 connections (Water Environment Federation, 2008) and 150 – 200 connections (Buchanan et al., 2010). The more capacity of the vacuum station is in use the lower the costs per connection (Buchanan et al., 2010) and the higher the population density gets the less competitive vacuum sewer system becomes. Cost saving factor of the vacuum sewer system is the network. High flows require relatively huge vacuum stations and parallel vacuum sewer pipes (Elawwad et al., 2014).

The price of the vacuum sewer system depends on the material selection. Collection chamber price depends on the type of the collection chamber and on the installation depth of the collection chamber. Typically the costs per connection decreases when more than one house is connected to the same collection chamber. Costs of the vacuum station vary for example depending on the control system requirements, location of the project and zoning requirements (Water Environment Federation, 2008).

2.6.1 Construction

Cost estimation for the installation, materials and maintenance of a vacuum sewer system are presented in Table 7. The comparison is done for an area of 200 households. The costs of the systems include collection chambers for every connection, system piping, vacuum pumps, discharge pumps and all additional appurtenances. It is assumed that the topography is relatively flat, the contractor would charge 20 % for profit and overhead and there are no sales taxes on materials. Professional services such as engineer fees are not included in the costs. It is assumed that one collection chamber serve at least two households and wastewater sources are about 60 m apart. House connection sewer installations are paid by the house owners (Buchanan et al., 2010).

Table 7. *Estimated costs of vacuum sewer system (Buchanan et al., 2010). Exchange rate 1 € = 1,09 $, March 2016.*

Cost Factor	House Connection to Collection Chamber	Collection Network Cost (100 Collection Chambers)
Materials and Installation		
($)	1800 – 2700	1869000 – 2804000
(€)	1650 – 2480	1718000 – 2578000
Annual Electricity		
($)		9500 – 14000
(€)		8740 – 12880
Annual O&M		
($)	16 – 24	82000 – 123000
(€)	15 – 22	75400 – 113200
60 Year Life Cycle Cost – present value		
($, 2009)		4775000 – 7162000
(€)		4387000 – 6581000

However, actual costs will vary significantly from the costs presented in Table 7 depending on site conditions and local economics (Buchanan et al., 2010).

Vacuum sewers are feasible and cheaper than conventional sewers in many situations, according to vacuum sewer system companies. In the areas of flat ground a gravity sewer system needs to install pumping stations to avoid the trenches to become deep. The installation and maintenance of pumping stations can be expensive. In addition, in the areas where there is running sand, high water table or rock close to the ground surface it is expensive and difficult to dig deep trenches for the gravity sewer system (Elawwad et al., 2014).

There is not information if the construction costs of vacuum sewer system are lower than the construction costs of gravity sewer system. One aspect is that vacuum sewer system has lower capital costs for construction compared to the gravity sewer system (Little, 2004). Another aspect is that typically the construction cost of vacuum sewers is somewhere between the costs of gravity and pressure sewer construction costs (Water Environment Federation, 2008).

The capital costs for vacuum sewer system construction are considered lower due to smaller pipe diameter, shallower trenching (requires less excavation) (Little, 2004; Shammas & Wang, 2010; Masteller & Moler, Inc, 2013: EPA, 1991), no need for manholes, less pumping and less lift stations (Little, 2004), ability to avoid unexpected obstacles (due to saw-tooth profile) (Sekisui Chemical, 2015; Shammas & Wang, 2010). In addition, the construction costs of vacuum sewer system are lower than costs of conventional sewer system in certain soil conditions that are unstable soil, rock and high water table and the vacuum sewer system cost may be lower in restricted construction zones and in flat areas (Shammas & Wang, 2010).

Detailed hydraulic designs were done for conventional and vacuum sewer systems in 28 chosen agricultural villages in Egypt in a study of Cairo University. A comparison was done for both of the sewer systems by using statistical analysis. The result was that the total vacuum sewer system and gravity sewer system costs depends on the population and area variable. The investment costs of vacuum sewer system were lower than the investment costs of gravity sewer system. Vacuum sewer system was a good competitor to conventional systems in areas with high groundwater table and in flat areas, from financial point of view. The investment costs also depended on whether the local market supplies the construction equipment, especially collection chambers, or not (Elawwad et al., 2014).

A Sanitary Sewer Feasibility Study and Report for North Sebastian area of Indian River County, USA, has been prepared (Masteller & Moler, Inc, 2013). The study estimated the construction costs of the proposed centralized sewer system. Costs of three different sewer systems were compared (Table 8).

Table 8. *Construction cost comparison of gravity, vacuum and low pressure sewer system (Masteller & Moler, Inc, 2013). Exchange rate 1 € = 1,08 $, March 2016.*

Sewer System Alternative	Costs ($)	Costs (€)
Gravity Sewer System	5000000	4590000
Vacuum Collection System	6600000	6060000
Low Pressure Pump System (Grinder Pump)	8600000	7900000
Low Pressure Pump System (STEP)	7100000	6520000

The construction costs of gravity sewer system are lower than the construction costs of vacuum sewer system in North Sebastian area of Indian River County, USA, based on the study (Masteller & Moler, Inc, 2013).

2.6.2 Operation and Maintenance

There is not information if the operation and maintenance costs in vacuum sewer system are lower than in gravity sewer system. Cost estimation for the maintenance of a vacuum sewer system is provided in Table 7. Operation and maintenance costs of the vacuum sewer system are related to the vacuum station which involves the electrical costs and maintenance costs of vacuum pumps, discharge pumps and stand-by generator.

One aspect is that the operation and maintenance costs are often higher for vacuum sewer system than for a gravity sewer system (Masteller & Moler, Inc, 2013; Schubert et al, 2003) due to the high number of mechanical element in use, higher electrical costs and due to need for oversight personnel to monitor the system (Masteller & Moler, Inc, 2013). Another aspect is that the maintenance costs of vacuum sewer system are lower due to the self-cleaning velocities of the pipes that results in less maintenance required compared to the gravity sewer system (Beauclair, 2010).

Electricity costs for vacuum sewer system are reported to be 1.66 – 3.34 $ per month per connection. Larger stations have typically lower power consumption per connection. Electricity costs are mainly composed of using the vacuum and discharge pumps and part of the energy costs is the fuel required to operate stand-by generator during the power failure (Buchanan et al., 2010). In addition, electricity is required for heating and ventilation (Water Environment Federation, 2008).

Life cycle replacement costs are expected to be higher in vacuum sewer system than in conventional systems. The costs are higher in vacuum sewer system because it has a lower life expectancy than conventional system (Masteller & Moler, Inc, 2013). Life expectancy of vacuum sewer system is 15 - 25 years (Buchanan et al., 2010).

2.7 Case Studies

2.7.1 General Information

In this section are presented general information regarding studied vacuum sewer systems that are located in Poland (Miszta-Kruk, 2015), South-Africa (Armitage et al., 2010; Taing et al., 2011) and rural Alaska (Schubert et al., 2003). Three vacuum sewer systems with similar conditions were studied in Poland and one system that was located in an informal settlement called Kosovo in Cape Town was studied in South-Africa. There are 15000 inhabitants in Kosovo. In rural Alaska there is a vacuum sewer system located in a town called Savoonga, which is a traditional Siberian Yupik Eskimo village with population of ~700. Table 9 presents general information about the systems.

Table 9. *General information regarding vacuum sewer systems in Poland, South-Africa and Alaska. ND= no data.*

	Poland (Miszta-Kruk, 2015)	**Cape Town, South-Africa** [1] Taing et al., 2011 [2] Armitage et al., 2010	**Savoonga, Alaska** (Schubert et al., 2003)
Amount of the Systems	3	1 [1]	1
Households/Toilets Connected to the System	ND	ND/345 [1]	170/ND
Amount of the Chambers	130-278	43? [1]	ND
Pipe Material	PE	uPVC [2]	HDPE
Pipe Diameter (mm)	90-280	90-160 [2] Houseconnection 110 [2]	100-150
Length (m)	2800-12500	ND	ND
Commissioning Year	2002	2009 [1]	1997

The systems were commissioned between the years 1997 and 2009 (Table 9). The vacuum sewer system was found suitable for Kosovo, because of the flat ground, sandy soil and high groundwater table. In addition, the settlement is dense: only little space between the buildings (Taing et al., 2011). In Savoonga the soil is shallow, thaw unstable silt with high moisture content. There is also rock over shallow bedrock. Due to these conditions an above ground utilidor system that is supported on timber sills was selected. The outbox utilidors are used for freeze protection in some systems in Alaska. They can be built at ground level, elevated or buried. Deep excavation might be challenging due to the permafrost. However, buried utilities are in general preferred in Alaska.

Due to the cold climate, material selection, heat loss prevention and methods of freeze protection are considered in the design of the systems in Alaska. In Savoonga the service lines for water and vacuum sewer lines are located in the same trench to prevent the vacuum sewer line from freezing by the heat from circulating water service lines. Also heat tape is installed to allow thawing. Also in many cases in Alaska the interface valves are located inside the house to protect them from freezing.

There are two vacuum pumps in Savoonga. The type of the vacuum pump is Busch rotary vane vacuum pump. The size of the vacuum tank is 3m^3 and the vacuum generated by the vacuum pumps is -0,53 - -0,66 bars in Savoonga. There is no data available regarding the type of the vacuum pumps, volume of the vacuum tank and pressure of the system in Poland or Kosovo.

The amount of toilets connected to the system in Kosovo is 345. They are located in 43 blocks (Taing et al., 2011). The amount of collection chambers in the systems in Poland vary between 130 and 278. In Kosovo there are 43 blocks and each block has its own collection chamber that has concrete rings with lockable lids as a security feature to protect collection chambers from damage (Taing et al., 2011). There is no data available regarding the amount of toilets or collection chambers connected to the system in Savoonga and the amount of households connected to the vacuum sewer systems in Poland.

The pipe material is PE in all the systems in Poland, uPVC in Kosovo (Armitage et al., 2010) and HDPE in Savoonga. HDPE is durable for repeated freezing and thawing cycles. In general in Alaska, typically the inner part is HDPE and the outer part can be HDPE or corrugated metal pipe. The outer part is for protecting the pipe during the installation or reduces the risk of damage for above ground installations.

2.7.2 Challenges

In this section are compared the challenges faced with the vacuum sewer systems in Poland (Miszta-Kruk, 2015) and South-Africa (Taing et al., 2011). Table 10 presents the comparison of the failures events. There were no data available regarding the challenges of vacuum sewer systems in Alaska.

In Kosovo (Cape Town, South-Africa) the toilets functioned only couple of weeks before the first blockages and overflowing took place. The blockages were due to too small outlet pipes for the items that uneducated users flushed through the toilets. For anal cleansing was used cement, flour sack paper and newspapers (Beauclair, 2010). In general, the lack of maintenance and user education, and technical defect were the main cause of the failures (Taing et al., 2011). In addition, it was used cheap building materials for the system due to vandalisms and insufficient budget (Beauclair, 2010). In 2011 the system was functioning as 40 l conservancy tanks that were being emptied three times a week (Taing et al., 2011).

Collection chamber failures have been experienced in Poland and Kosovo. Collection chamber failures were the most common failures in the vacuums sewer systems in Poland. The failure was typically related to the interfaces valves. The most common collection chamber failures (92 % of the cases) were failures to open an interface valve or to close it tightly, defective valve closing mechanism and flooded valve controller. Other failures occurring in collection chamber were clogging of the suction pipe by solid contaminants, wrong proportions of air/waste, clogging the vent pipes and freezing valve. The probability level of operation of a collection chamber with interface valve was 50% after less than 2 months.

Table 10. *Failures in the vacuum sewer systems in Poland and Cape Town. Y=yes and ND= no data.*

	Poland (Miszta-Kruk, 2015)	**Cape Town, South-Africa** [1] Taing et al., 2011 [2] Armitage et al., 2010 [3] Beauclair, 2010
Failures Experienced with:		
Collection Chamber	Y	Y [2]
Vacuum Pumps	Y	Y [1]
Vacuum Tank	ND	ND
Discharge Pumps	ND	ND
Vacuum Sewers	ND	ND
Leakages in the System	Y	Y [1]
Blockages in the System	ND	Y [3]
Failures Caused by:		
Users	Y	Y [1]
Maintenance	ND	Y [1]
Material Defect	Y	Y [1]
Storm water	ND	Y [2]

The sewage was overflowing back to the drains and surrounding of the collection chamber since the beginning of the operation in Kosovo. The collection chambers had been blocked by large amount of solids including newspaper, bricks, sticks and leaflets. The solids also blocked sensor pipes and therefore the sensors were constantly indicating that the valves are open. The result was continuously closed valve (Armitage et al., 2010).

Overworking of vacuum pumps have been experienced in Poland and in Kosovo. It was the most common failure in the vacuum station in Poland. The failure was caused by leakages in the system. Also events of power failure resulted in pump failures or shutting down the entire system (Miszta-Kruk, 2015). The vacuum pumps have overworked due to the leakages in the system also in Kosovo (Taing et al., 2011).

The users were responsible for about 25 % of the failures of the vacuum sewer system by improper use of the system in Poland. However, the most common cause (47 % of the cases) was material defect, such as a defect of an interface valve element mechanism that opens or closes the valve (Miszta-Kruk, 2015). In addition, storm water has caused damage on the system in Kosovo (Armitage et al., 2010).

The vacuum sewer system has been poorly managed by the users also in Kosovo. The residents were not educated to use the system and they disposed items such as cutlery and brick into the vacuum sewer system. Sharp objects resulted piercing interface valve diaphragms and some collection chamber sumps were filled with gross solids. The valve controllers malfunctioned due to fat and dirt clogging the sensor pipe and due to the failure to open the valve the chambers over-filled of sewage (Taing et al., 2011). Also the poverty of the users affects on the functioning of the system. The users could not always afford for the toilet paper and therefore they used newspaper or other improper material for anal cleansing (Armitage et al., 2010).

The maintenance of the system by the service providers has been poor in Kosovo. There have been technical, social and institutional constrains that have decreased the effective municipal management. It was not clear who had responsibility to manage the system. The personnel had limited technical knowledge and there was no plan for the operation and maintenance of the system. The personnel did not receive adequate training. The maintenance team lacked capacity and spare parts, especially sensors and valves that were not locally available (Taing et al., 2011).

Solutions for the failures in Kosovo are suggested to be procuring appropriate anal cleansing materials, educating the users, providing locks and keys for the toilets, allocating each communal block to a specific set of households, periodic training workshops for the maintenance personnel, installation of solids interceptor tanks directly before the collection chambers, collection chamber level monitoring by paid residents or installation of level indicators in the collection chambers and use of durable materials for construction (Armitage et al., 2010).

It was learnt from the case of Kosovo that infrastructural pilot project plans need an extensive period for monitoring, evaluating and adaptative troubleshooting. In addition, the success of the sanitation technologies is contextually bound to how they are planned, managed and locally adopted. In addition, due to the experience in Kosovo, the system has considered to be more suitable for areas that enjoy good solid waste disposal services and regularly use soft, biodegradable anal cleaners such as toilet paper (Taing et al., 2011). From the case of Poland was learnt that in order to improve the operation of sewer systems, the technical awareness of the residents to properly use waste water disposal installations should be improved and the working parameters of sewer system elements should be monitored constantly (Mista-Kruk, 2015).

3. MATERIALS AND METHODS

A two month field trip was done in Namibia in October and November 2014. The working base was in Ondangwa Town Council, but also one week field trip to Gobabis, Henties Bay, Kalkrand and Stampriet was conducted. The main methods for collecting research data regarding the vacuum sewer system in the LA's in Namibia were literary survey, making observations on the field and semi- structured interviews. In addition, one day visit to three Estonian vacuum sewer systems was done in October 2015. The methods used in Estonia were semi-structured interviews and observations.

3.1 Literature Survey

The majority of the time during the field trip in Namibia was spent on investigating data regarding vacuum sewer system in Ondangwa Town Council. This data includes letters, faxes, e-mails, design drawings, minutes of the meetings and other notes. The data was mostly archived in a folder called " Fast Track 2006 Replacement Sewer 2006/7" in the Technical Department of Ondangwa Town Council.

Part of the data regarding the challenges with the vacuum sewer systems in Gobabis, Henties Bay, Kalkrand and Stampriet was gathered from literature. The source of the data was internet archives of Desert Research Foundation of Namibia (DRFN).

3.2 Semi-structured Interview

Semi-structured interview means an interview that does not have strict questions, but the topics are known. It is a method between using clearly structured query forms and open discussion. For this thesis was interviewed about 25 persons in Namibia and Estonia (Table 11) using semi-structured interview. Interviews related vacuum sewer systems in Namibia were carried out with staff and officers of companies (Afcon, Consulting Services Afrcia (CSA), Preferred Management Services (PMS) and Flovac Estonia) and councils (Ondangwa, Gobabis, Henties Bay Kalkrand and Stampriet).

Table 11. Persons interviewed for the results of the thesis.

Interviewed Person	Organization	Subject	Topic
Cioccolanti, M.	PMS	Ondangwa vacuum sewer system	Motive for the vacuum sewer system
Finance Department Officer	Ondangwa Town Council	Technical Department of Ondangwa Town Council	Annual budget
Human Recourses Officer	Ondangwa Town Council	Ondangwa Town Council	Town Council, organization and technical services
Kandongo, E.	CSA	Ondangwa vacuum sewer system	Motive for the vacuum sewer system, design, construction
Kurz, E.	Afcon cc	Ondangwa vacuum sewer system	Main Components, design, construction, operation and maintenance, failures
Lefasi, E.	Henties Bay Municipality Council	Henties bay vacuum sewer system	General information, failures
Robinson, J.	Ondangwa Town Council	Technical services	Drinking water services
Sarap, G.	Flovac Nordic Oü	Estonian vacuum sewer systems	General information and operation experiences
Shatiwa, J.	Ondangwa Town Council	Ondangwa vacuum sewer system, technical services	Wastewater services, motive for the vacuum sewer system, main components, design, operation and maintenance
Shidiwe, P.	Ondangwa Town Council	Ondangwa vacuum sewer system, technical services	Wastewater and drinking water services, motive for the vacuum sewer system, main components, design, operation and maintenance
Technical Department Personnel	Gobabis Municipality Council	Gobabis vacuum sewer system	General information, failures
Technical Department Personnel	Kalkrand Village Council	Kalkrand vacuum sewer system	General information, failures
Technical Department Personnel	Stampriet Village Council	Kalkrand vacuum sewer system	General information, failures
Tulenheimo, R.	Ondangwa Town Council	Ondangwa Town Council	Technical services

Some of the personal communications were done via e-mails (Table 12).

Table 12. *Personal communication via e-mail for the results of the thesis.*

E-mailed Person	Company	Subject	Topic
Iihuhwa, K.	Ondangwa Town Council	Town of Ondangwa	Museum information, town profile
Naukushu, R.	Ondangwa Town Council	Town of Ondangwa	Ondangwa map (Figure 4), Ondangwa valuation roll

3.3 Observation

The observations were done for the vacuum sewer systems in Namibia (Ondangwa, Gobabis, Henties Bay, Kalkrand and Stampriet) and in Estonia (Leppneeme, Vääna-Jõesuu and Viimsi). The Namibian LAs Gobabis, Henties Bay, Kalkrand and Stampriet introduced the vacuum stations and the collection chambers of the systems. In Estonia it was also introduced the vacuum stations and collection chambers of the system.

In Ondangwa it was done more detailed observations on the vacuum sewer system by checking all the collection chambers marked on the draft design drawings. In addition, the vacuum station was visited. However, it was not possible to observe the vacuum sewer system leakages or blockages due to broken vacuum pumps and lack of equipment. In Estonia the two operating vacuum sewer systems (Leppneeme and Vääna-Jõesuu) and the construction site of vacuum sewer system in Viimsi were introduced.

3.4 Town of Ondangwa

The town of Ondangwa (Figure 4) was established in the 1840's as missionary center of the Finnish Missionary Society. From 1970's until 1990, the independence of Namibia, the town was used as a strategic location and administration center for the South African defense forces. Since 1998 the town has been an autonomous town.

Figure 4. *A map of Ondangwa.*

Current challenges faced in Ondangwa are demand of houses and unemployment. Most of the infrastructure is poor, especially roads and housing. At the moment, lot of houses are being constructed and the Town Council is busy making serviced plots available. In November 2014 there were 5779 plots in Ondangwa and 1995 people on the plot queue.

Ondangwa is located in Oshana Region, northern Namibia (Figure 5). It borders three regions: Oshana, Oshikoto and Ohangwena Regions. The area of Ondangwa is 5323 hectares. Amount of urban localities in 2011 in Ondangwa was 22822 (Table 13). The total population of Ondangwa covered about 21 % of the total population of Oshana Region. Number of private households in Ondangwa was 7559 and average size of a household was 4.3 persons (NSA, 2014a). Based on the population growth rates (Table 13), Ondangwa is one of the fastest growing town in Oshana region (NSA, 2014a).

Table 13. Population and population growth rate of Ondangwa and Oshana Region (NSA, 2014a).

	Ondangwa	Oshana Region
Population (2011)	36846	176674
Population Growth Rate (%, 2011)	1.5	09

Figure 5. *Location of Ondangwa and Oshana Region (Google, 2016).*

The climate is semi-arid in Ondangwa. The average annual rainfall is 400-500 mm and the mean annual evaporation is 2600-2800 mm per annum. During the rainy season occurs floods (DRFN, 2011h). Most of the rainfall occurs on summer months. The summers are hot and the winters are warm. The mean temperature in summer is 31.7 °C and in winter (June/July) the minimum temperature is 8.7 °C.

3.4.1 Town Council and Organization

In Namibia there is a three-tier system of governance including central government, Regional Councils and Local Authorities (Municipalities, Towns and Villages). Ondangwa is declared as “Town”, according to Local Authorization Act (1992, Schedule 1, 96). Due to that it has a Town Council which consists of seven members. Number of permanent staff in Ondangwa Town Council is 64. Sometimes there is not enough staff available for the biggest projects of the Technical Department. In that case the working power is found from the community and a ”one man contractor” – contract is used.

3.4.2 Technical Services

The responsibilities of the Technical Services department are mechanical services, water and sewage, electricity, roads, storm water, infrastructure, town planning, and fire and emergency services. Information regarding the educational background of the staff of the Technical Services was not available. All the positions of the Technical Services department were not filled in November 2014. Table 14 presents the annual budget of sewerage and water supply in 2014-2015.

Table 14. *Capital budget of sewerage and water supply in 2014-2015. Exchange rate 1€ = 17.2 N$, March 2016.*

Description of Capital Project	Amount (N$)	Amount (€)
Sewarage		
Services jj Location (Sewerage, Water, Pump Station, Roads)	9000000	523500
Services Informal Settlements	4000000	232600
Water Supply		
Stormwater Drainage System	500000	29100
Elevated Water Tower	2000000	116300
Services (Ext 6)	4000000	232600
Total	**19500000**	**1133700**

The total annual budget of Technical Services was 49800000 N$ (2894600 €, March 2016). The annual budget of sewerage and water supply was 39.1 % of the total annual budget of Technical Services.

3.4.3 Drinking Water Services

The first drinking water pipelines were built in 1960's to Old Ondangwa and Oluno. The used material was asbestos cement. The first pipelines of the new settlements were built in 1994-1996. In the new settlements the pipe material is PVC. In Oluno the pipe sizes are 50-160 mm and in Old Ondangwa 50-200 mm. The pipe size of the main ring is 200 mm and subsupply 110 mm and 160 mm. In November 2014, the Town Council was building new extensions and therefore also new water networks. All the new pipelines were PVC-pipes, and old asbestos cement pipes were replaced with PVC-pipes when they break down. House connections were made of galvanized pipes.

The source of the drinking water is Kunene River and the water is treated in Oshakati Water Treatment Plant. The treatment plant belongs Namibia Water Corporation Ltd (NamWater). NamWater is a commercial entity that supplies water in bulk to municipalities, industries and the Directorate of Rural Water Supply in the Ministry of Agriculture, Water and Forestry (NamWater, 2016).

The capacity of the Oshakati Treatment Plant is 2000 m^3/h and 40000 m^3 daily. It serves large areas of Oshana, Oshikoto and Ohangwena Regions. The treatment steps are chemical dosing, flash mixing, flocculation, settling, filtration and disinfection. From the treatment plant the water is pumped to larger reservoirs and from the reservoirs the water is transferred into various pipelines (NamWater, 2016). The only pumps of the water distribution network of Ondangwa are in the reservoir of NamWater from where the water is pumped to the water distribution network of Ondangwa.

There are five water towers in the town. Two of them are located in Oluno, and one to Extension 3 (near open market), airport and Old Ondangwa (reservoirs of NamWater). The pressure of water distribution network is usually 3 bars. However, the pressure is too low at times and therefore there is a plan to build four new water towers in some of the new extensions and also to Oluno for the prison and army base.

90% of the households had access to safe drinking water in 2011 (Table 15) (NSA, 2014a). The main challenges of the water distribution network are old pipelines in Oluno and lack of water. NamWater is not always able to deliver enough water, therefore Ondangwa needs own water reservoir for storing the water for the case of water cut.

Table 15. *Households and population by main source of water for drinking/cooking in Ondangwa in 2011 (NSA, 2014a).*

Source of Water for Drinking/Cooking	Households	Population
Total	7559	32814
Piped Water Inside	2929	14421
Piped Water Outside	2118	8358
Public Pipe	1675	6265
Borehole with Tank Covered	42	213
Borehole with Open Tank	69	313
River/Dam/Stream	341	1510
Canal	90	419
Well Protected	34	195
Well Unprotected	94	450
Other	167	670

To the water distribution network were connected 3683 households in November 2014 (Finance Department Officer, personal communication, November, 2014). However, the number in Table 15 (piped water inside or outside) is bigger than the number provided by Finance Department Officer of Ondangwa Town Council. The reason for it might be that one water source is shared by many households and only one household is registered as a user of the source.

3.4.4 Wastewater Services

The first wastewater pipelines were built in 1960's to Old Ondangwa and Oluno. Material of the first pipelines was asbestos cement and earthwire pipe. The first pipelines of new settlements were built in 1994-1996. The pipe material in the new settlement was uPVC. In Oluno the pipe sizes are 110mm and in Old Ondangwa 160mm and 200mm. In November 2014, Town Council was building new extensions and therefore also new sewer lines. In addition, the Council was replacing some old sewer lines in Oluno. All the new pipelines are made of uPVC-pipes.

The town is using two different wastewater systems, gravity sewer system and vacuum sewer system. Vacuum sewer system covers two extensions: extension 1 Oluno and extension 4 Old Ondangwa. In these two extensions part of the houses is connected to the vacuum sewer system and part of them is connected back to the old gravity sewer system. The rest of the town is using gravity sewer system. 60 % of the households had a toilet facility in 2011 (Table 16) (NSA, 2014a).

There are 22 gravity sewer system pump stations in Ondangwa and new pump stations will be coming on the new extensions. The area of Ondangwa is relatively flat and therefore the pump stations are located densely. Due to the flat ground also the manholes in Ondangwa are 4-6 m deep at the deepest points.

The pump stations need lot of maintenance because of sand entering the system. In addition, during the rainy season most of the manholes flood. Every 1-2 weeks the pipes experience blockages because of cooking oil, stones and plastic bottles, and because people throw rubbish to the manholes. In November 2014, the hydro blaster used for blockages was malfunctioning. In addition, the Council did not have enough staff to maintain the sewer system.

From the sewer network the wastewater is lead to the oxidation ponds located south of Oluno without no treatment. The volume of wastewater is unknown because there are no meters. The oxidation ponds were built in 2006 as a part of the Fast Track Project. The oxidation ponds consist of two identical lines. The original purpose was to use only one line at time, but at the moment the both lines are used at the same time. One line has two collection chambers and four square shaped primary oxidation ponds. The rounded main oxidation pond, the earth dam, is shared by the both lines. The collection chambers are equipped with grids and sand separation.

Table 16. *Households and population by main type of toilet facility in Ondangwa in 2011 (NSA, 2014a).*

Source of Toilet Facility	Households	Population
Total	7559	32814
Private Flush Connected to Sewer	1432	6135
Shared Flush Connected to Sewer	582	2018
Private Flush Connected to Septic/Cesspool	193	930
Shared Flush Connected to Septic/Cesspool	139	576
Pit Latrine with Ventilation Pipe	449	2060
Covered Pit Latrine without Ventilation Pipe	920	4593
Uncovered Pit Latrine without Ventilation Pipe	615	3148
Bucket Toilet	200	1098
No Toilet Facility	3011	12209
Other	18	56

To the sewer line were connected 2984 households were in November 2014 (Finance Department Officer, personal communication, November, 2014). The number in Table 16 (private and shared flush connected to sewer) is smaller than the number provided by Finance Department Officer of Ondangwa Town Council. The reason might be that the sewer reticulation system has expanded to cover more households between the years 2011 and 2014.

3.5 Other Field Work Areas

Namibian LA's Gobabis, Henties Bay, Kalkrand and Stampriet were visited for the results of the thesis (Figure 6; Table 17). Gobabis and Henties Bay are declared as a "Part 2 Municipality" and have municipality councils whereas Kalkrand and Stampriet are declared as a "Village " and have village councils (ALAN, 2015). The number of people working in technical departments of the Councils vary between 3 and 20.

Table 17. *General information regarding Henties Bay, Gobabis, Stampriet and Kalkrand. [1] NSA, 2014b [2] ALAN, 2015 [3] NSA, 2014c [4] DRFN, 2011d [5] Kalkrand Technical Department, personal communication, October 2014 [6] DRFN, 2011g.*

	Henties Bay	Gobabis	Kalkrand	Stampriet
Population	4720 [1]	20993 [1]	~3000-5000 [5]	2835 [4]
Local Authority	Part 2 Municipality [2]	Part 2 Municipality [2]	Village [2]	Village [2]
Region	Erongo [1]	Omaheke [1]	Hardap [6]	Hardap [4]

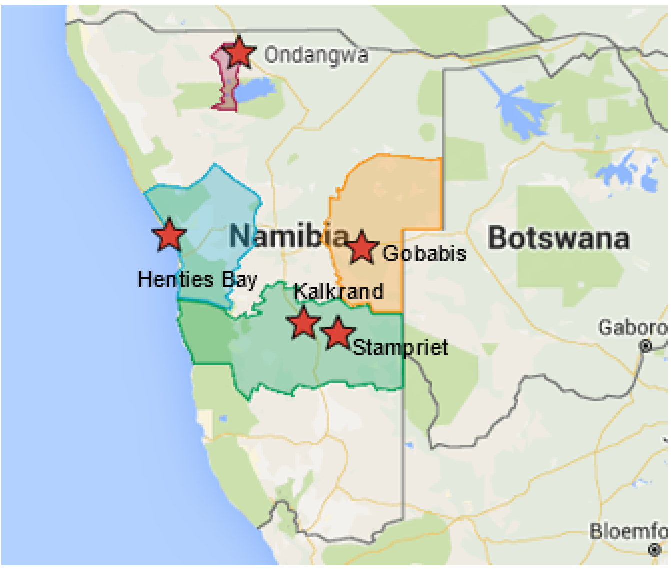

Figure 6. *The locations of Gobabis, Henties Bay, Kalkrand and Stampriet (Google, 2016).*

Population of Henties Bay was 4720 in 2011 (NSA, 2014b). However, the population of Henties Bay changes seasonally. During holiday season the population is ~20000 (DRFN, 2011f). In other LA's the population does not change seasonally.

4. VACUUM SEWER SYSTEM IN ONDANGWA

The vacuum sewer system in Ondangwa have faced lot of challenges from the design to the maintenance stage. The main components of the system and the factors that affect on the functioning of the system were studied.

4.1 Motive for the Vacuum Sewer System

The vacuum sewer system project in Ondangwa was a development project ran under a Ministry of Regional and Local Government, Housing and Rural Development and it was managed by PMS. The project was initiated in 2006. The four key components of the project were: replacement of gravity sewers in Oluno (extenstion 1) and Old Ondangwa (extension 4), renovation/ de-commissioning and construction of new oxidation ponds, upgrading of existing sewer pump stations and replacement of sewer pumping mains (Fast Track Project Documents, 2006-2010). In this thesis is focused only on one component of the Fast Track project, the replacement of gravity sewers in Oluno and Old Ondangwa.

Funding for project came from the ministry of Regional and Local Government, Housing and Rural Development. The ministry has Regional Development and Equity Fund. It focused on funding the improvements of civil infrastructure of LA's. Sanitation is a part of civil infrastructure. Ondangwa Town presented to the Regional Development and Equity Fund their needs, and got funding for the four key components of the Fast Track project.

Replacement of sewerline in Oluno and Old Ondangwa was needed because of the age and the condition of the existing gravity sewer lines. The asbestos cement sewer reticulations in Oluno and Old Ondangwa were built in 1960's and at the beginning of the Fast Track Project the sewers were more than 40 years old and not functioning properly. For example many blockages were experienced with the system. There were two alternatives for replacement of gravity sewers in Oluno and Old Ondangwa, a new gravity sewer system and a vacuum sewer system. After comparing gravity sewer system and vacuum sewer system it was decided to construct vacuum sewer system to the side of the existing gravity sewers in Oluno and Old Ondangwa.

The stuff of Technical Department of Ondangwa Town Council would have been familiar with gravity sewer system, but on the other hand the total cost of vacuum sewer system was less than 25 % the cost of gravity sewer system. A gravity sewer system also requires deep trenches up to six meters due to the flat ground in Ondangwa. Excavating six meters deep is challenging in the built area and between existing houses. In addition, a new road was built in Ondangwa by government's money few years before the beginning of Fast Track project. A big part of the new road would have been damaged due to the excavating of gravity sewer system. The budget of the Fast Track project is shown in Table 18 and 19. The prices are excluding Value Added Tax (VAT) (Fast Track Project Documents, 2006-2010).

Table 18. *Estimated construction costs, 2006 (Fast Track Project Documents, 2006-2010). Exchange rate 1 € = 16.9 N$, March 2016.*

Construction Costs	**N$**	**€**
Ponds	5395900	319300
Vacuum Sewer	8611500	509600
Pumping Main	3490600	206600
Mechanical/Pump Stations	3562100	210900
Operation & Maintenance	2000000	118500
Contingency	-	-

Table 19. *Estimated total costs, 2006 (Fast Track Project Documents, 2006-2010). Exchange rate 1 € = 16.9 N$, March 2016.*

Total Costs	**N$**	**€**
Total Construction	23060000	1365800
Total Soft Costs*	4077200	241600
Total Project Cost	27137200	1608200

*Engineering, consulting, management, accounting, travel, etc.

The costs of operation and maintenance are divided between all the four key components of the project. The total installation cost of vacuum sewer line was N$8611462.45 (500400 €, March 2016), while the total costs of the whole Fast Track project was N$ 27137239.85 (1578100 €, March 2016) (Fast Track Project Documents, 2006-2010).

4.2 Results

The main components of the vacuum sewer system (Figure 7; Table 20) were analyzed and the failures during the design, construction and operation and maintenance stage. There were various failures in the main components of the vacuum sewer system. They were caused by poor design, construction, maintenance, improper use of the system, vandalism and material defect. In addition, also the environment and climate conditions caused failures on the vacuum sewer system.

Table 20. *Components and features of the vacuum sewer system in Ondangwa.*

Component	Oluno	Old Ondangwa	Total
Vacuum Stations (No.)	0	1	1
Vacuum Tanks (No.)	0	1	1
Vacuum Pumps (No.)	0	4	4
Discharge Pumps (No.)	0	2	2
Collection Chambers (No.)	~66	~69	~135
Length of the Network (m)	~4260	~4470	~10540
Vacuum Sewer Material	class 9 uPVC	class 9 uPVC	
Vacuum Sewer Diameter (mm)	75, 90, 110 and 160	75, 90, 110 and 160	

Figure 7. *A draft of the vacuum sewer system in Ondangwa.*

Main components of the system are a vacuum station, collection chambers and vacuum sewer line (Table 20, Figure 7).Many of the numbers in Table 20 are estimations due to lack of proper documentation and lack of as-built drawings of the vacuum sewer system in Ondangwa.

4.2.1 Vacuum Station

The vacuum station is located in Old Ondangwa, due to the central location of the suburb in Ondangwa. The original plan was to connect more extensions to the vacuum sewers system. The components of the vacuum station are a vacuum tank, four vacuum pumps and two discharge pumps (Table 21). In addition, there is an SPS type control panel for controlling the vacuum system (Pierdolla, 2007) and a stand-by generator in case of power failures. The door of the vacuum station was not locked in October 2014 and therefore the vacuum station was unprotected against vandalism.

Table 21. *Main components of the vacuum station and the failures and condition in November 2014. ND=no data.*

Component	Number	Type	Previous Failures	Condition in November 2014
Vacuum Tank	1	Nirosta (Pty) Ltd	ND	Functioning
Vacuum Pumps	4	RoeBusch Vacuum Pump RC0250D, RA 0250 D 5Z1 CWZZ	Continuous Running	All the pumps broken
Discharge Pumps	2	Fygt Sewage Pump, DN 100 PN 10	Blockages	Functioning

The type of the vacuum tank is vertical. The working pressure is 10 kPa and the test pressure is 100 kPa. Filling levels of the vacuum tank are listed in Table 22 (Pierdolla, 2007).

Table 22. *Filling levels of the vacuum tank (Pierdolla, 2007).*

Action	Filling Level (m)
d=1,8 m Measuring Range	0-2.8
Vacuum off	1.2
Prealarm	0.9
Discharge Pump on	0.75
Discharge Pump off	0.6

The vacuum pumps are equipped with a three-phase-motor 400 Volt. The power of the pumps are 5.5 kW and the revolution of the pumps is 1500 U/min. The vacuum pumps were programmed to work in cycles (Table 23) (Pierdolla, 2007).

Table 23. *Vacuum pump working pressures (Pierdolla, 2007).*

Function	Basic Adjustment
Minimum	-0.3
Pump 4 on	Entf.
Pump 3 on	-0.48
Pump 2 on	-0.5
Pump 1 on	-0.52
All Pumps off	-0.6
Maximum	-0.8

In the past at times the vacuum pumps have been running continuously, due to the inability to form negative pressure of -0.6 bars. For example leakages in the vacuum sewer lines might block the system to reach required negative pressure. In addition, in one pump the soft-start was not functioning. None of the fours pumps were operating in November 2014 (Table 21). The pump failures are probably caused by lack of the maintenance and the continuous running of the pumps might have broken them down.

The discharge pumps are equipped with a three-phase-motor 690/400 Volt. The power of the pumps are 2.4 kW and the revolution of the pumps is 1460 U/min. The sewage is pumped from the vacuum station first to the Fysal pump station and then to Oluno to the oxidation ponds. The discharge pumps are programmed to turn on when the filling level of the vacuum tank is 0.75 m and turn off when the filling level is 0.60 m (Table 22) (Pierdolla, 2007).

The filling levels of vacuum tank and cycles of vacuum pumps are programmed to the SPS type control panel. The panel can also give for example information regarding the process schematic and maintenance hours. In addition, it is possible to set alarms to the panel. The alarm can for example indicate a failure in the system (Pierdolla, 2007). The alarm system is not used in Ondangwa. In addition, there is a stand-by generator in the vacuum station for the case of power failures, but the generator is not working. Power failures have been experienced frequently in Ondangwa (DRFN, 2011e).

4.2.2 Collection Chambers

It is installed 66 collection chambers in Oluno and 69 in Old Ondangwa. To each chamber is connected 4-6 houses. Recommended maximum number of houses connected to one chamber is 4 which means that some of the collection chambers are designed to be overloaded. The numbers are estimated due to the lack of as-built drawings. Many of the chambers were flooding, filled with debris or broken in November 2014.

The type of the collection chambers is ROEVAC-Collection Chamber G 65 2 1/2" with Valve Unit 65 mm, Passenger load Version-Standard Chamber, designed by Roediger and made of Polyethylene, Medium Density (PE-MD) material (Pierdolla, 2007). The four main components of the installed collection chambers are valve chamber, chamber piping, house connection and ROEVAC-cover (Figure 8; Table 24).

Table 24. *Components of collection chamber and the previous failures and condition in November 2014.*

Component	Previous Failures	Condition in November 2014
Valve Chamber	Controller failures due to moisture Blockages in interface valves Storm water infiltration	Assumed that majority of the controllers and interface valves are malfunctioning
Chamber Piping	Blockages	Unknown
House Connection	Blockages Backflow into individual houses	Unknown
Cover	Broken	Majority of them are broken

The valve chamber consist of thermal insulation layer, valve unit with controller, isolation plug service-Wye and rubber elbow with sump stack hose. The valve chamber is separated from the sump for sewage collection and is housing only the valve unit (Pierdolla, 2007).

Chamber piping consists of service elbow pipe, horizontal suction pipe assembly and vacuum service line (Pierdolla, 2007). The gravity lines from houses to collection chambers are made of class 6 pipes with a diameter of 110mm (Fast Track Project Documents, 2006-2010). House connection consists of sump, T-Fitting (PVC-KG) for gravity line, PVC (KG)-pipe as well as straight coupling (6x6) (Pierdolla, 2007). The size of the suction pipe is 65 mm, which is too small to the local conditions. People flush too big obstacles through the toilet. Since the gravity lines (house connections) from houses to the chambers has diameter of 110 mm, the obstacles usually go through them and do not get stuck until the suction pipe.

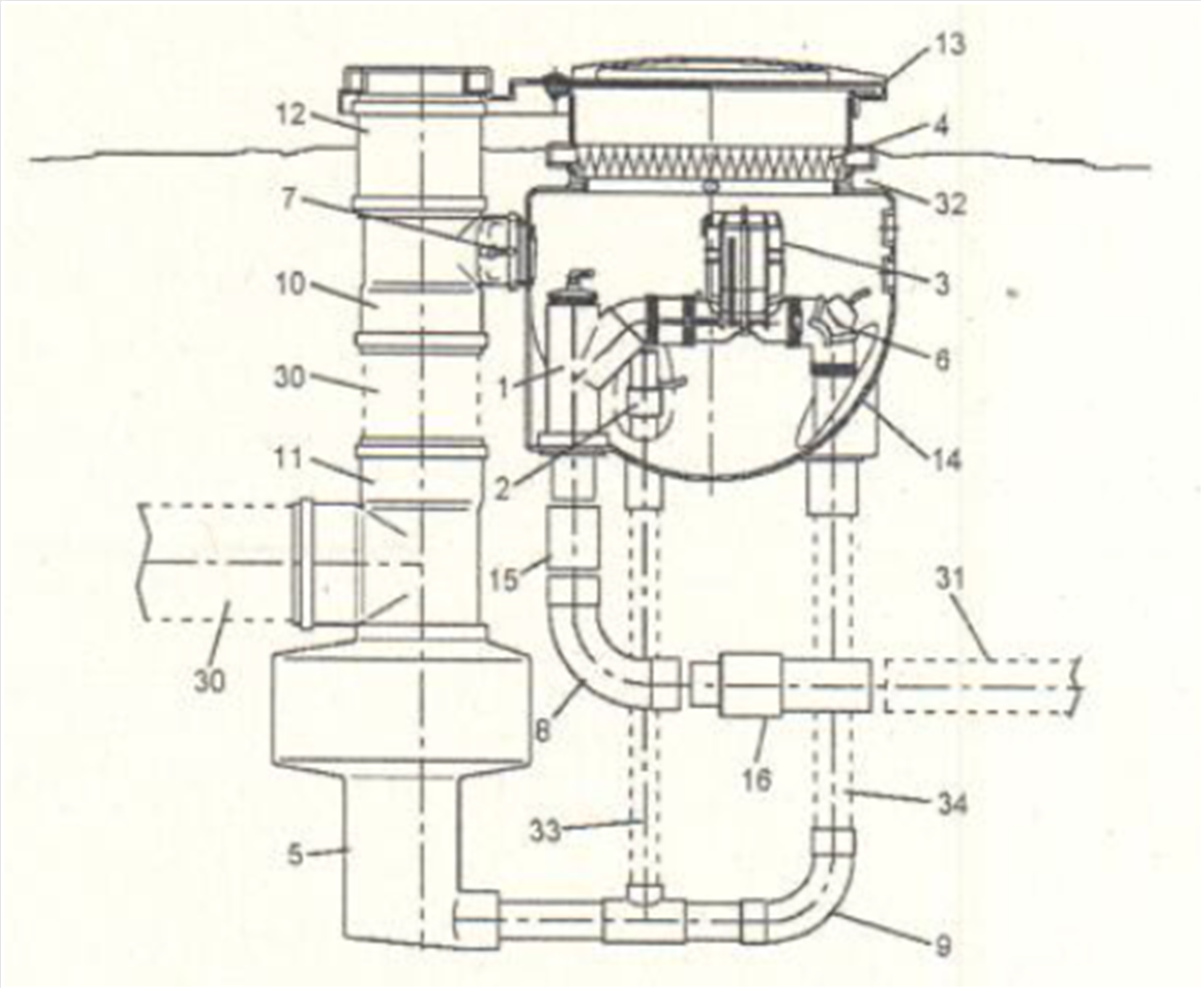

__Figure 8.__ Roediger collection chamber type G 65 2 ½" passenger load. 1. Service-Wye with Vacuum Intake Plug, 2.Sensor Cap, 3. Valve Unit, 4. Isolation Layer, 5. Sump-65, 6. Rubber Elbow with Air Admittance Tube, 7. Barbed Fitting for Air Admittance Tube, 8. Bend, 90 deg. Long sweep, PVC solvent weld, 9. Horizontal Suction Pipe Assembly, 10. Reducer Tee, PVC-KG, DN 200/100, gasketed, 11. Tee, PVC-KG, DN 200/200, gasketed, 12. Couplilng PVC-KG, DN 200, gasketed, 13. Valve Chamber-Lid passable with Gasket, 14. Valve Chamber, 15. Coupling, 16. Transition Coupling PVC/PE (only if required if service line is PE), 30. Pipe PVC-KG DN 200, 31. Vacuum Service Line, 32. Concrete Bearing Edge for Antiflotation Ring, 33. Vertical Suction pipe d 50 PN 10, 34. PVC Pressure Pipe d 63 PN 10 (Pierdolla, 2007).

ROEVAC cover is lockable, passenger load and made of PE-MD (Pierdolla, 2007). At the beginning the chambers were not locked with metal covers and people threw obstacles like stones into the chambers and caused malfunctioning of the system. The locks were installed to avoid vandalism. However, the locks were destroyed and only few of the chambers were locked and protected against vandalism in November 2014.

The standard valve chamber is splash-proof, but not flood-proof (Pierdolla, 2007). Since flood occurs occasionally, the standard chamber have not been suitable for the local conditions. In addition, some of the collection chambers were installed in too low level (DRFN, 2011e). The storm water has entered the chambers. Later concrete protection rings were built to the chambers in case of rain event to avoid infiltration in the valve chamber (Fast Track Project Documents, 2006-2010). The concrete protection rings did help reduce the amount of storm water entering the chambers but did no resolve the failure completely.

4.2.3 Vacuum Sewer Line

According to the design drawings the vacuum sewer network consists of class 9 uPVC pipes with diameters of 75, 90, 110 and 160 mm. The diameter of the main line between Oluno and Old Ondangwa is 160 mm. The size of the pipelines is too small to the local conditions since households are not educated well. They flush too big obstacles through the toilets and block the vacuum sewers (Table 25).

Table 25. *Component of vacuum sewer network and previous failures and condition in November 2014. ND=no data.*

Component	Previous Failures	Condition in November 2014
Vacuum Sewers	Blockages, Leakages, Damaged by excavation	Leakages, No data regarding blockages
Inspection Pipes	ND	Under soil

The length of the vacuum sewer network in Oluno is estimated to be 4.3 km and in Old Ondangwa 4.5 km. The length of the main line between Oluno and Old Ondangwa is 1.2 km. The trenches are 1.6 m deep at the deepest point. In addition, there are inspection pipes that are marked with yellow poles along the sewer line. Some of the inspection pipes were under the soil in November 2014. However, there were no as-built drawing available in the Ondangwa Town Council and therefore the numbers are estimations.

The original plan was to connect 800 houses to the vacuum sewer system. Finally 480 houses were connected to the system. Some households of the original plan did not want to be connected to the system due to numerous failures faced with the system. The system was not operating November 2014, and Town Council has connected some houses (of the 480) in Oluno and in Old Oldangwa back to the old gravity sewer line. Town Council has a list of the houses connected back to the old gravity sewer system. When a household complains about the sewer system blockages the council re-connects the household back to the old gravity system. According to the house list, 103 houses were connected back to the gravity sewer system in Oluno and 10 houses in Old Ondangwa. However, the list is not complete.

Town Council has been told that the whole Oluno was already connected back to old gravity sewer system but during observations done by the fieldwork of this thesis, 12 chambers were found flooding and there were still houses connected to the vacuum sewer system in that area. The sewerage was not sucked out of the chambers with the septic truck because Town Council was not aware that there were flooding chambers.

The vacuum sewer network has been damaged several times accidentally when excavating for some other services in the same trench (Figure 9). All the cases are not reported to the Town Council. It is suspected that there is a leakage somewhere in the main line caused during a construction of a road and therefore the vacuum sewer system is not functioning properly in Oluno. The vacuum sewer network is not marked and therefore not protected from these accidents.

Figure 9. *A damaged vacuum sewer in a trench in Old Ondangwa.*

There is also an air admittance station located in Oluno. The key of the air admittance station is lost and therefore it is not possible to go inside the building and make observations.

4.2.4 Design

Two designs were done for the vacuum sewer system, both of them by same company. The first design done in 2006 had insufficiencies and inadequacies. Therefore part of the vacuum sewer system had to be re-designed in 2009. There were three main failures faced with the first design:

1. the system was designed on top of the existing services
2. there was no proper survey done on the land
3. storm water was not taken into account when designing the system

The vacuum layout plan was designed to run on top of the existing structures (water pipes and other existing services). The laying of the vacuum sewers to the indicated levels on the long section was not possible in Oluno. For the same reason it was challenging to lay the collection chambers to the levels as indicated (Fast Track Project Documents, 2006-2010). In addition, there was no proper survey done on the topography of the land before plans and drawings were produced by the engineer and before the project was handed over to the contractor. Therefore in several instances collection chambers were to be sited in higher grounds than the houses that they are supposed to serve (Fast Track Project Documents, 2006-2010).

Storm water was not taken into account when designing the system. There were failures regarding the installation height of the collection chambers especially with the chambers that were built in low lying areas. Even though the design of the system caters for a certain amount of rain water, it is not designed for storm water. In order to avoid infiltration in the valve chamber body in case of rain events, the top of the collection chamber needs to overlap the concrete protection ring (Fast Track Project Documents, 2006-2010). Concrete protection rings were constructed for the chambers. They reduced the amount of storm water entering the system but did not remove the failure completely.

The lacks of the first design were solved by making a new design. The critical sections in Oluno and the main line from Oluno to vacuum station were re-designed. Although the area of Old Ondangwa was working properly, the profiles were corrected in that area as well (Fast Track Project Documents, 2006-2010). The second design was based on new land surveys. There was a small modification necessary in the area of Old Ondangwa due to a different main road crossing related to the vacuum line coming from Oluno. This minor change was not critical to the operation of the system. In Oluno the positions of the chambers and the house connections did not change. The new drawings only have different levels and different positions of the lifts of the saw-tooth profile (Fast Track Project Documents, 2006-2010).

4.2.5 Construction

The construction of the vacuum sewer system started in November 2006 and finished in 2010 (DRFN, 2011e; Fast Track Project Documents, 2006-2010). The construction progress was slower than planned due to challenges experienced during the construction. The contractors did not have experience of constructing a vacuum sewer system.

Failures occurred especially during the laying of the pipes. The pipes were not laid properly because it was discovered existing services which clash with the proposed position of the lines. Other failures during the laying of pipes were wrong pipes delivered on site, a lot of open trenches which were water logged and collapsing on the sides, the trenches were not compacted to acceptable standard and the solvent cement specified for connections was not used. Wrong kind of solvent cement caused leakages in the system. Also it was found out obstacles like concrete and stones inside the pipe diameter. It was suspected that these obstacles block the quick recovery of the vacuum at the end of the line. In addition, there were inspection pipes installed improperly (Fast Track Project Documents, 2006-2010).

As-built drawings had a significant variation on the mainline from Oluno to the vacuum station in Old Ondangwa. The design had 13 lifts of size 20-30 cm and as-built drawings 25 lifts and the sizes of the lifts were unclear. This change was considered critical to the functioning of the system (Fast Track Project Documents, 2006-2010). Proper laying of the pipes is critical for the functioning of the system. If pipes were not laid exactly in accordance to the designed profiles within the given max tolerance of ±12 mm, any kind of vacuum sewer would not be able to function properly (Fast Track Project Documents, 2006-2010). Finally the pipes were re-laid.

There were broken communication links between Town Council and planners, and between contractor and planners in 2011. The current standards regarding installation seemed to be unknown. There was no formal quality management on site. The contractor was left alone with all quality and installation challenges. There were no as-built and as-tested records forthcoming (DRFN, 2011e).

4.2.6 Operation and Maintenance

The vacuum sewer system started to operate in 2009. The system operated well the first three months, but after that, it started to face failures, chambers started to overflow and the controllers of the valve units malfunction. In November 2014 the system stopped to operate due to broken vacuum pumps. The system was maintained since it started to operate until beginning of the year 2014 by the second contractor. Since the beginning of the year 2014 the maintenance was done by Technical Department of Ondangwa Town Council. During the maintenance period of the contractor the contractor companied with the Town Council (Fast Track Project Documents, 2006-2010).

Maintenance of the system has been inadequate and challenging. Main challenges have been lack of the maintenance skills, lack of proper tools, and delay and price of the spare part supply (Table 26). In addition, vandalism and malfunctioning of the vacuum sewer systems make the maintenance more challenging.

Table 26. *Information regarding the operators of the vacuum sewer system in Ondangwa. Y=yes and N=no.*

	2009-2014	**2014**
No. of Operators	1 person (possible to expand)	2 persons
Education	Y	N
Schedule	Y	N
Spare Parts in Access	N	N
Enough Tools	Y	N

The maintenance tasks have not been in accordance with the recommendations of preventative maintenance tasks of the designer. Due to the malfunctioning vacuum sewer system there have been a constant need of emergency maintenance since the system started to operate. The maintenance before year 2014 included daily checking of the controllers from each chamber and checking of the oil levels of the pumps at the vacuum station. At some point, the vacuum pumps ran continuously and due to that the vacuum pumps had been turned on and off daily. In this case, daily means from Monday to Friday. Every six months the vacuum tank and discharge pumps were cleaned and the vacuum pumps were serviced every year.

The main maintenance tasks since the beginning of 2014 have been emptying flooding chambers with a septic truck. The operator did not have a complete list of the houses connected back to the old gravity sewer system and therefore all the flooding collection chambers were not known. The septic truck brake down on the last week of October 2014. Since that the Council has been busy to install houses of Oluno and Old Ondangwa back to the old gravity sewer system.

The valve controllers need to be changed frequently because they break down frequently in the local conditions and due to the malfunctioning system. The challenge with the controllers have been the price and the availability. The operators did not have spare parts in access and the spare parts were ordered when needed from Germany. Before the year 2014 the operators did not lack maintenance tools. They had some basic tools. Since the year 2014 the operators have lacked proper tools for the maintenance

There was a lockable store room and workshop in 2011. The workshop was appropriate equipped to carry out variety of maintenance work. Monitoring and evaluation existed and occupational health and safety policies too, but they were not fully implemented (DRFN, 2011).

5. VACUUM SEWER SYSTEM IN NAMIBIA

Besides of Ondangwa there are also other LA's in Namibia that have or have had a vacuum sewer system. These LA's are Gibeon, Gobabis, Henties Bay, Kalkrand, Outapi and Stampriet. For this thesis was visited four LA's (Gobabis, Henties Bay, Kalkrand and Stampriet) to get general knowledge about the vacuum sewer system in Namibia and for comparison purpose with the Ondangwa system. The visits were done in October 2014.

All the vacuum sewer systems in these LA's were designed by the same company. The vacuum sewer systems in different LA's were constructed by different contractors. In most cases, the Ministry of Regional and Local Government, Housing and Rural Development played the major role in decision making, for the initiation of the vacuum sewer systems in the councils and it provided the funds.

Generally, very few of the LA's were satisfied with the vacuum sewer system. Most of the councils with the system were not happy with the system and were planning to replace it with the gravity sewer system. Some council such as Ondangwa have an option, to connect back to the old gravity sewer system whereas, other councils such as Kalkrand and Stampriet have no other option, but to do their level best to maintain the vacuum sewer system.

The vacuum sewer system of Gibeon was not visited for this thesis because it was not operating anymore in November 2014. It had been replaced by another sewer system, due to various failures faced with the vacuum sewer system. The system of Outapi was not either visited for this thesis. However, the system in Outapi was operating and it was the newest vacuum sewer system in Namibia.

5.1 Vacuum Sewer Systems

The vacuum sewer system is the only municipal sewer system in Kalkrand and Stampriet. However, some households use septic tanks in Stampriet. 2070 households and 80 - 90% of the suburbs are connected to the vacuum sewer system in Kalkrand. The vacuum sewer system covers one extension (Extension 3) out of nine extensions of the municipality in Gobabis. The 3 extension is in an informal settlement. The vacuum sewer system covers Extensions 4, 6 and 10 in Henties Bay. They are high income areas.

The vacuum sewer system was chosen to Extension 3 in Gobabis and to Extensions 4, 6 and 10 in Henties Bay due to flat ground in these extensions. The ground of the extensions is also sandy in Henties Bay (DRFN, 2011a, 2011f). In addition, the vacuum sewer system was considered to be the cheapest option in Stampriet.

The systems have been installed between the years 2001 and 2010 (Table 27). The oldest system operates in Kalkrand whereas the newest systems operate in Henties Bay and Gobabis. All the systems were designed by the same company (DRFN, 2011b, 2011c). The contractor of the systems in Henties Bay, Stampriet and Kalkrand was the same company and in Gobabis the construction was done by Municipality. The maintenance was done by the Councils of the LA's. The size of the maintenance team vary between 4 and 2 persons. The biggest maintenance team was in Henties Bay whereas the smallest team was in Gobabis. The work power can be extended if needed in Henties Bay. The provision of spare parts and consumables was done through the same company and the spare parts were supplied from Germany (DRNF, 2011c).

Table 27. *General information regarding vacuum sewer systems in Namibia. [1] Gobabis Techical Department, Ocotber 2014 [2] Henties Bay Techical Department, October 2014 [3] Kalkrand Technical Department, October 2014 [4] Stampriet Technical Department October, 2014 [5] DRFN, 2011c [6] DRFN, 2011b.*

	Gobabis	**Henties Bay**	**Kalkrand**	**Stampriet**
No. of Households	180 [1]	~800 [2]	376 (80%) [3]	317 (70%) [4]
Installation Year	2008-2010 [1]	2008 [2]	2001 [3]	2008-2010 [4]
Maintenance by	Council, 2 persons [1]	Council, 4 persons [2]	Council, 3 persons [3]	Council [4]
No. of Vacuum Pumps	2 [1]	4 [2]	3 [3]	3 [4]
No. of Vacuum Tanks	1 [1]	1 [2]	1 [3]	1 [4]
No. of Discharge Pumps	2 [1]	2 [2]	2 [3]	2 [4]
Size of Interface Valve (mm)	75 [2]	90 [2]	75 [2]	75 [2]
Future Plans	Replace by gravity sewer system [1]	Improve maintenance [2]	Improve maintenance [3]	Replace by gravity sewer system [4]

Number of households connected to the systems vary between 180 and 800. Gobabis had the smallest amount of households connected to the system and Henties Bay had the biggest amount of households connected to the system. However, the system can be extended to accommodate 1500 households in Gobabis.

Number of collection chambers was 68 in Henties Bay. However, in the original plan the number of collection chambers was smaller. More collection chambers have been installed to decrease the amount of houses connected to one chamber. There are more than 170 chambers in Stampriet. Number of houses connected to one chamber sometimes exceeded the recommendation of four houses in each chamber in Henties Bay, Kalkrand and Stampriet. The number of houses connected to one chamber was 5-10 in Henties Bay, up to seven in Kalkrand and up to five in Stampriet.

In the vacuum station the amount of vacuum tanks and the amount discharge pumps were the same in all of the systems. The amount of vacuum pumps vary between 2 and 4. The smallest capacity of pumps was in Gobabis and the biggest capacity of pumps was in Henties Bay.

5.2 Challenges

All the systems had operational issues during the observation in October 2014. The challenges have been similar between all the LA's. Failures have occurred in the systems at least since 2011. However, any major challenges did not occur in the vacuum sewer system in Henties Bay in 2011 (DRFN, 2011f).

The major challenges for the operators and communities have been the installation and management of vacuum sewer systems. In addition, the lack of technology integration, meaning flood and vandal protection, was the key management issue leading to dysfunctional systems. Due to the dysfunctional systems the operators and communities are often exposed to health risks (DRFN, 2013c). The failures started since the commission of the vacuum sewer system in Stampriet and the system operated approximately 2 years without failures in Kalkrand. After constructing more than 300 toilets more the failures started, due to the bigger load in the system.

Based on the observations done for this thesis, the main challenges mentioned by the LA's were spare part delivery (Stampriet, Kalkrand, Henties Bay, Gobabis), lack of funds to protect and maintain the system (Stampriet, Kalkrand), lack of stand-by generator (Kalkrand), vandalism (Kalkrand, Gobabis), lack of tools (Gobabis), malfunctioning of the vacuum pumps (Henties Bay), poor installation (Henties Bay) and lack of user education (Kalkrand).

5.2.1 Vacuum Station

Failures in vacuum station components have occurred in all of the LA's (Table 28). Most of the failures have been experienced in the vacuum pumps. In addition, the lack of stand-by generator and blockages of discharge pumps have been issues. Vacuum tank failures were the least common failures in the vacuum sewer systems in all of the LA's. However lot solids such as bones, rags, newspaper, glass and plastic have been found in the vacuum tanks in Kalkrand and Stampriet in 2012 (Table 28) (DRFN, 2012).

The vacuum pumps malfunctioned in all of the LA's in October 2014. Two pumps in Henties Bay, and one pump in Kalkrand were not operating. All the pump were operating in Gobabis, but not properly. In addition, in all the LA's the vacuum pumps were running continuously in 2014. They could not reach the turn off level vacuum. The pumps were ran manually in Gobabis. It means that the maintenance team turned them on and off daily. The pumps run continuously due to too small vacuum pump capacity and leakages in the vacuum sewers in Henties Bay. There have been also vacuum pump failures before the observations (Table 28).

Discharge pump failures have occurred in most of the LA's (Table 28). Only one discharge pump was operating in Stampriet and Kalkrand in October 2014. In addition, there have been discharge pump blockages at times in Henties Bay, Kalkrand and Stampriet (DRFN, 2011c, 2012). Solids such as bones, rags, newspaper, glass and plastic were found from the discharge pumps in Kalkrand and Stampriet in 2012 (DRFN, 2012).

Table 28. *Failures in the vacuum stations in Gobabis, Henties Bay, Kalkrand and Stampriet, and in Ondangwa for comparison purposes. Y= yes, N=no and ND=no data. [1] DRFN, 2012, [2] DRFN, 2011c [3] DRFN, 2011f [4] DRFN, 2011b.*

Challenges	Gobabis	Henties Bay	Kalkrand	Stampriet	Ondangwa
Vacuum Tank	**ND**	**ND**	**Y**	**Y**	**N**
Solids Inside					
Observation (2014)	N	N	N	N	N
General	ND	ND	Y [1]	Y [1]	N
Vacuum Pumps	**Y**	**Y**	**Y**	**Y**	**Y**
Broken Pumps					
Observation (2014)	N	Y	Y	N	Y
General	ND	ND	Y [2]	Y [1]	Y
Continuous Run					
Observation (2014)	Y	Y	Y	Y	N
General	ND	Y [3]	Y [2]	Y [4]	Y
Discharge Pumps	**ND**	**Y**	**Y**	**Y**	**Y**
Broken Pumps					
Observation (2014)	N	N	Y	Y	N
General	ND	ND	ND	ND	N
Blockages					
Onservation (2014)	N	Y	N	N	N
General	ND	Y [1]	Y [1,2]	Y [1]	Y
Stand-by Generator	**Y**	**Y**	**Y**	**Y**	**Y**
Does Not Exist					
Observation (2014)	ND	ND	Y	ND	N
General	Y [1]	Y [1, 3]	Y [1]	Y [1]	N
Does Not Function					
Observation (2014)	ND	ND	ND	ND	Y
General	-	-	-	-	Y

Lack of stand-by generator have been an issue in all of the LA's (Table 28). There was no stand-by generator in Kalkrand and the events of power failures were said to be one of the main challenges in October 2014. Sometimes in the event of a power failure the chambers are flooded of sewage and the sewage ends up on the streets. The power failures were common at least in Gobabis and Kalkrand in 2011 (DRFN, 2011a, 2011c).

5.2.2 Vacuum Sewers and Collection Chambers

Vacuum sewers and collection chamber failures have occurred in all of the LA's (Table 29). In vacuum sewers the typical failures are blockages or leakages that result in poor vacuum build-up. The collection chambers failures are typically blockages, flooding or malfunctioning interface valves or valve controllers. Vacuum sewer failures have occurred in all of the LA's. Blockages occurred at times in Gobabis, Kalkrand and Stampriet in October 2014. There were leakages in the sewers in Henties Bay in October 2014. There have been also vacuum sewer failures before, for example numerous vacuum leaks in Gobabis in 2012 due to UV exposure of pipes in open trenches (DRFN, 2012).

Poor vacuum build-up occurred in all of the LA's in October 2014. Permanent running of vacuum pumps without stabilizing an appropriate vacuum have occurred also before (Table 29). The result was overflowing of collection chambers in Henties Bay and sometimes the vacuum has been too low to trigger the valve controller in Kalkrand (DRFN, 2011c). In addition, there have been a vacuum loss in suction pipes in Stampriet and Kalkrand in 2011 resulting water logging and loss of system viability (DRFN, 2011b).

Collection chamber failures have occurred in all of the LA's. However, the collection chambers were functioning well in Henties Bay and Kalkrand in October 2014, whereas the collection chambers were flooding because of too low vacuum in the system in Gobabis and Stampriet. In Gobabis it was due to the fact that all the interface valves had been removed and replaced by pipe. The system was not sealed anymore. Frequent blockages of collection chambers have occurred in Gobabis, Kalkrand and Stampriet before the observations (DRFN, 2012). Around 20 % of the collection sumps were blocked in Stampriet and 30% in Kalkrand in 2012 (DRFN, 2012). Lots of solids such as newspaper, rag, bottles, shoes, bones, glass and stones were found in the sumps in Gobabis, Kalkrand and Stampriet.

Valve controller failures have occurred in all of the LA's (Table 29). The valve controllers break easily if they are in contact with water or dust (DRFN, 2011b). The broken controller keep an interface valve open continuously. Most of the valve controllers have been flooded during rainy season in Stampriet in 2011 (DRFN, 2011b). In addition, vacuum valve controllers have been sensitivity to dust in Kalkrand and Stampriet.

There have been also interface failures in the systems (Table 29). However, there were no interface valves anymore in the collection chambers in Gobabis in October 2014. All the interface valves have been replaced by normal pipes in Gobabis. The interface valves have had failures in Stampriet (DRFN, 2011b) and Kalkrand (DRFN, 2011c) in 2011 and they had to be cleaned and exchanged frequently.

Table 29. *Failures in the vacuum sewers and collection chambers in Gobabis, Henties Bay, Kalkrand and Stampriet, and Ondangwa for comparison purposes. Y=yes, N=no and ND= no data. [1] DRFN, 2012 [2] DRFN, 2011b [3] DRFN, 2011c [4] DRFN, 2011f.*

Challenges	Gobabis	Henties Bay	Kalkrand	Stampriet	Ondangwa
Vacuum Sewers	**Y**	**Y**	**Y**	**Y**	**Y**
Leakages					
Observation (2014)	ND	Y	ND	N	Y
General	Y [1]	ND	ND	Y [2]	Y
Blockages					
Observation (2014)	Y (at times)	ND	Y (at times)	Y (at times)	ND
General	ND	ND	Y [3]	ND	Y
Poor Vacuum Build-up					
Observation (2014)	Y	Y	Y	Y	Y
General	ND	Y [4]	Y [3]	Y [2]	Y
Collection Chambers	**Y**	**Y**	**Y**	**Y**	**Y**
Valve Controller	(no valves)				
Observation (2014)	-	Y	ND	Y	ND
General	ND	ND	Y [1]	Y [1, 2]	Y
Interface Valve	(no valves)				
Observation (2014)	-	ND	ND	ND	ND
General	ND	ND	Y [3]	Y [2]	Y
Blockages	Frequent	Rarely	frequent	frequent	
Observation (2014)	ND	ND	ND	Y	ND
General	Y [1]	Y [4]	Y [1]	Y [1]	Y
Flooding					
Observation (2014)	Y	N	N	Y	ND
General	Y [1]	ND	Y [3]	Y [1,2]	Y
Storm Water					
Observation (2014)	ND	ND	ND	ND	ND
General	ND	ND	Y [3]	Y [2]	Y

Flooding of the collection chambers have occurred in most of the LA's (Table 29). Flooding results often in interface valve failures. The collection chambers were flooding in Gobabis and Stampriet in October 2014 because of too low vacuum in the system. There have been also before frequent flooding of the collection chambers in the LA's.

Flooding sewage had caused health risk to users and operators in Stampriet and Kalkrand in 2011. In addition, odor nuisance caused by the sewage attracts snakes, flies and rodents in Stampriet (DRFN, 2011b, 2011c). Overload of the collection chambers have occurred in Henties Bay, Kalkrand and Stampriet. In one collection chamber has been connected more than 4 houses. It might result in flooding of the chamber.

Storm water have caused flooding of the chambers in Stampriet and in Kalkrand resulting flooded valve controllers (DRFN, 2011b, 2011c). There is no storm water collection system in Henties Bay and therefore storm water might cause flooding of the chambers (DRFN, 2011f). Heavy rains might cause floods that might result in flooding collection chamber sumps in Gobabis in 2011 (DRFN, 2011a). However, in October 2014 the personnel of Technical Department in Gobabis mentioned that failures caused by storm water have not occurred. In the rainy season the main line is covered by water and it makes the maintenance difficult in Stampriet.

5.2.3 Users and Vandalism

Vandalism have occurred in all of the LA's (Table 30). The three key interfaces between the users and vacuum sewer technology have been the collection sumps, bathroom facilities and protruding components such as division valves and inspection/vacuum test points DRFN (2011g). Typically there have been excessive solids entry (bottles, shoes, stones) into the system directly through the collection sumps and through the respective bathroom facilities. In addition, opening the collection chamber lids and breaking the system exists. In addition, people have open the lids of collection chambers in Kalkrand and Stampriet, and cut the fence of vacuum station and damage inspection pipes in Stampriet (DRFN, 2011b, 2011c).

The result of vandalism (too big solids flushed or thrown into collection sumps) have been blockages in Henties Bay, Stampriet (DRFN, 2011b) and Kalkrand. Vandalism has caused pump failures in Gobabis and damaged components (inspection pipes) in Stampriet (DRFN, 2011b). The impacts of vandalism have been the smallest in Henties Bay, because the system is installed in high income area. Vandalism has been the main cause of collection chamber blockages in Stampriet (DRFN, 2012). Anal cleansing materials also cause blockages in the system. People use newspaper and rags in Gobabis (DRFN, 2012). The Council share toilet papers to people to avoid using other materials for anal-cleansing in Kalkrand in October 2014.

Vandalisms can be limited by designed-in protection and user education. The user education regarding the vacuum sewer system has been minimal in all of the LA's. In addition the chambers are not protected against vandalism, traffic, flood or dust (DRFN, 2011b, 2011f, 2012). The chambers are not locked and therefore people can open the lids easily and dump solid waste in the collection chambers. In addition, the vacuum station lacked protection in Kalkrand in 2011 (DRFN 2011c).

Table 30. *The forms of vandalism in Gobabis, Henties Bay, Kalkrand and Stampriet. Y=yes, N=no, ND=no data. [1] DRFN, 2012 [2] DRFN, 2011b [3] DRFN, 2011c.*

Challenges	Gobabis	Henties Bay	Kalkrand	Stampriet	Ondangwa
Type					
Solids to Sump	Y [1]	ND	Y	Y [2]	Y
Big Obstacles Flushed	ND	Y [2]	ND	Y [2]	Y
Broken Components	ND	ND	ND	Y	Y
Prevention					
User Education	Basic [1]	ND	Basic [1]	Basic [1]	N
Protection of the Chambers	N	N	N	N	Y
Waste Separation at Source	ND	ND	N [3]	ND	ND

The users were not educated how to use the system properly in Kalkrand and Stampriet in October 2014. Only basic education has been provided in Gobabis, Kalkrand and Stampriet in 2012 (DRFN, 2012). The lack of user education and integration have been seen as a reason for the vandalism in Stampriet (DRFN, 2011b). Lack of waste separation at source (DRFN, 2011c) and lack of playgrounds for kids are also seen as a reason for vandalism in Kalkrand. The children play with stones and open the collection chamber lids and throw the stones inside.

5.2.4 Maintenance

Maintenance has been inadequate and challenging in all of the LA's. Main challenges were lack of the maintenance skills, lack of proper tools, and delay and price of the spare part supply (Table 31). In addition, vandalism and malfunctioning of the vacuum sewer systems make the maintenance more challenging.

Lack of maintenance capacity has occurred in all the LA's (DRFN, 2011f, 2012 2013a). There was an urgent need of operation and maintenance capacity building and technology integration to minimize vandalism in Gobabis, Kalkrand and Stampriet in 2012 (DRFN, 2012). It was not been clear who is in responsibility to maintain the system in Stampriet and Gobabis in 2013 (DRFN, 2013b).

Table 31. *Maintenance challenges in Gobabis, Henties Bay, Kalkrand and Stampriet, and Ondangwa for comparison purposes. Y=yes, N=no and ND= no data. [1] DRFN, 2011c [2] DRFN, 2011b [3] DRFN, 2011f [4] DRFN, 2011a [5] DRFN, 2011g [6] DRFN, 2013a [7] DRFN, 2012.*

Lack of	**Gobabis**	**Henties Bay**	**Kalkrand**	**Stampriet**	**Ondangwa**
Skills	Y	ND	Y [1]	Y [2]	Y
Capacity	Y [6,7]	Y [3]	Y [6,7]	Y [6,7]	Y
Training	Y [4]	N	Y [4]	Y [5]	Y
Tools	Y	Y	Y	Y	Y
Spare Parts	Y	Y	Y	Y	Y
Documentation	ND	ND	Y [1]	Y [2]	Y

The maintenance tasks have not been in accordance with the recommendations of preventative maintenance tasks of the designer. In all of the LA's there have been a constant need of emergency maintenance. The pumps were run manually in Gobabis October 2014. It means they were turned on and off daily. In addition, all the collection chambers were checked daily in Gobabis and Kalkrand. In case the system is not working the chambers were emptied chamber by chamber in Stampriet, and the maintenance personnel try to open blockages in chambers.

The common maintenance tasks in Stampriet and Kalkrand were exchanging interface valves and vacuum controllers, sucking out flooding chambers, removing solids from the sump and refitting opened lids in 2011 (DRFN 2011b, 2011c). There was a constant need of emergency maintenance (DRFN, 2011b). The collection sumps were de-blocked when people complain in Gobabis, and daily in Kalkrand and Stampriet in 2012. The valve controllers were fixed occasionally in Kalkrand and Stampriet (DRFN, 2012).

Maintenance skills were poor especially in Gobabis, Kalkrand and Stampriet in October 2014. However, the operators of all of the LA's have got a training, but not comprehensive enough. Maintenance personnel of Gobabis and Henties Bay have been trained by the vacuum sewer system company (DRFN, 2011a, 2011f. The personnel of Stampriet and Kalkrand have been trained by DRFN (DRFN, 2011g). However, according to the Technical Department Personnel in Stampriet, yet in October 2014 the maintenance personnel was not trained and skilled enough.

The main challenges with the spare parts were the high price and the delay on getting them. The LA's did not have spare parts in stock. The parts were supplied from Germany, and it takes about 6 months to supply a part (DRFN, 2012, 2011b). There was also a lack of proper maintenance tools in all of the LA's in October 2014. The operators were already poorly equipped with appropriate tools in Henties Bay, Kalkrand and Stampriet in 2011 (DRFN 2011b, 2011c, 2011f) and in Gobabis in 2012 (DRFN 2012).

Lack of documentation have been a challenge at least in Kalkrand and Stampriet in 2011 (DRFN, 2011b, 2011c). There was no monitoring, evaluation or record keeping. In addition, there were no as-built drawings in Kalkrand (DRFN, 2011c).

5.2.5 Installation

Installation failures have occurred in all of the LA's (DRFN, 2011d, 2013a). Some of the LA's have had challenges on operating the systems as a result from poor installation. Typically collection chamber bodies were installed below flood level. In addition, poor workmanship, inappropriate material use, poor availability of materials, laying pipes correctly and lack of supervision and quality assurance have been challenges during the installation of the system.

Poor workmanship has been an issue in Gobabis, Henties Bay, Kalkrand and Stampriet (DRFN, 2011b, 2011f). In addition, there was a lack of supervision and quality assurance in Henties Bay during the construction phase (DRFN, 2011f). Malfunctioning electricity connections was an issue in Stampriet after the commissioning of the system. The electicity connection installation was not done properly.

House connection have been an issue in Kalkrand due to the too small slope from a house to the collection chamber (DRFN, 2011c). Too shallow vacuum sewer trenches and lifts that are not up to standards were still issues in Henties Bay in October 2014. The installation was not done in accordance with the design in. In addition, pipes were not laid correctly in Gobabis.

Collection chambers have been installed below flood level in Gobabis (almost 90% of the chambers), Kalkrand (several chambers), Stampriet (several chambers) and Henties Bay (some collection chambers). The collection chamber bodies had to be raised afterwards. The chambers installed below flood level had caused submerged standard valve controllers. The chambers also experienced excessive solids entry due to vandalism and overflowed subsequently (DRFN, 2011f, 2013c).

In appropriate material use was an issue in Henties Bay, Kalkrand and Stampriet during the construction (DRFN, 2011b). The installation team did not have right fitting and therefore improvised in Henties Bay. The connections are not vacuum stable and therefore the vacuum pumps run continuously (DRFN, 2011f). There have been solvent weld fitting cracks in Stampriet and Kalkrand (DRFN, 2011b). Poor availability of materials during the installation was an issue in Gobabis.

6. DISCUSSION

The purpose of a sewer system is to transport sewage safely from the formation place to the treatment facilities. In the sewer systems the sewage is isolated from the surrounding on purpose to avoid health hazards and contamination of the environment, whereas in Namibia the malfunctioning vacuum sewer systems let the sewage leak to the environment and the people nearby the sewer systems and the operators are exposed on health risks. In addition, the environment is also exposed on contamination. In the vacuum sewer systems in Namibia the purpose of the vacuum sewer system is not fulfilled. Improvements are needed in all the LA's to decrease the contamination of environment and health risk of people. It was made a two month field trip in Namibia to observe the failures in the vacuum sewer systems and to interview people related to the vacuum sewer systems.

The LA's of Namibia have two options. They should either invest a lot on the improvements of the operation of the existing vacuum sewer systems or replace them with more applicable sewer system. In this study was only focused on the vacuum sewer system and therefore it is mainly given suggestions how to improve the operation of the vacuum sewer systems. However, the best solution might be replacing the existing vacuum sewer system by another sewer system.

Gravity sewer system would probably operate with less failures than vacuum sewer system in Ondangwa. It is more familiar to the sewer system operators and users, and it would probably withstand better the local conditions (for example too big obstacles flushed to the system by the users) due to bigger pipe sizes and better maintenance skills. Vacuum sewer system is more applicable to flat ground than gravity sewer system. The reason to choose a vacuum sewer system in Ondangwa was flat ground (and also price). In addition, vacuum sewer system is easier to install to urban areas due to shallower trenches compared to gravity sewer system. However, due to lack of skilled vacuum sewer system contractors the gravity sewer system installation could be more successful even though the system would require many pumping stations, deep trenches and the construction conditions are challenging.

Most probably a gravity sewer system would not either function up to standards in Ondangwa without improvements of the maintenance. Also conventional technologies have malfunctioned in Namibia, according to the analyses done regarding the water network and water loss management in Keetmanshoop, Namibia (Aalto, 2014, Tuovinen, 2014, Löppönen, 2011). One third of the water in the water network disappears and are non-revenue in Keetmanshoop. The causes have been old infrastructure and too high pressure that cause leakages in the pipes, water meter failures, illegal consumption, and also inadequate maintenance. Only visible leakages and customer reported failures are repaired and there is no record-keeping. The recommendations were improving the maintenance (training of the operators, long-term development plan, data collection, record keeping) and meters accuracy, locating and repairing the leakages, and pipe and shut valve replacements. Also better quality equipment and spare parts were recommended. Inadequate maintenance has been cause of failures also with conventional technologies, not only with vacuum sewer systems.

The vacuum sewer system in Ondangwa was compared to case studies of other vacuum sewer system. The vacuum sewer systems of the other cases are located in Poland (Miszta-Kruk, 2015) and South-Africa (Armitage et al., 2010; Taing et al., 2011). In Poland was studied three vacuum sewer systems with similar conditions and in South-Africa was studied a system that was located in an informal settlement called Kosovo in Cape Town. There are 15000 inhabitants in Kosovo.

There are similarities among the most common failures between the case studies and case Namibia. Collection chamber failures and overworking vacuum pumps have been common in Namibia, Poland and South-Africa. In all the three cases the collection chamber failures are typically related to the interface valves. In addition, the collection chambers have been blocked by large amount of solids and the collection chambers have been overflowing in South-Africa and Namibia. Overworking of vacuum pumps have been caused by leakages in the system In Namibia, Poland and South-Africa. The overworking of vacuum pumps was the most common failure in the vacuum stations in Poland. It was a common failure also in Namibia.

There are also similarities among the main causes of the failures between the case studies and case Namibia. The main causes have been the users, poor maintenance and technical failures. For about 25 % of the failures of the vacuum sewer system are caused by improper use of the system in Poland. The users cause failures due to lack of user education and poverty in Namibia and South-Africa. The users could not always afford for the toilet paper and therefore they used newspaper or other improper material for anal cleansing. Poor maintenance have caused failures on the systems in Namibia and South-Africa. In both cases the personnel lack proper training and therefore had limited technical knowledge regarding operation and maintenance of the system. Also in both cases the maintenance team lacked capacity and spare parts, especially sensors and valves that were not locally available.

The most common cause (47 % of the cases) was material defect, such as a defect of an interface valve element mechanism that opens or closes the valve in Poland. Material defect have caused failures also in Namibia and South-Africa. In case of Namibia it was difficult to point what failure was caused by component reliability and what was caused by the users or poor maintenance. However, the valve controllers are too sensitive components to the conditions of Namibia. In addition, storm water has caused damage on the system in Namibia and South-Africa.

It was also made a field trip to Estonia to visit three vacuum sewer systems in October 2015 for comparison purposes with the Namibian systems. Two of the vacuum sewer systems were operating (Leppneeme and Vääna-Jõesuu) and one system (Viimsi) was under construction. The connections per vacuum sewer system vary between 75 and 300. The vacuum sewer systems in these towns were designed by different company than the Namibian systems. All of the operating vacuum sewer systems were functioning well with minor failures. Typical failure with the systems were blockages due to too big obstacles in the piping system in Estonia. In addition, storm water was able to enter the system in some collection chambers (Sarap, personal communication, October 2015).

The outcome of the analyses done regarding the water network and water loss management in Keetmanshoop was an aspect that even conventional technologies as water networks do not function properly in Namibia. Some of the causes of the water network failures were similar to the causes of the vacuum sewer system failures: no long-term development plan, no record keeping, lack of training of the operators and lack of good quality equipment and spare parts. The conclusion is that the majority of the vacuum sewer system failures are due to the local conditions rather than due to the technology itself. Also the outcome of the trip to Estonia was an aspect that the failures in Namibia were not caused by the vacuum technology itself. Rather, the technology has not been adapted to the local conditions that are more challenging than in Estonia. The conclusion is that the vacuum sewer system operates better in developed regions than in developing regions.

6.1 Findings of the Study

The vacuum sewer systems in Namibia have had failures since the design phases. The failures have been faced in many fields: in the design, installation, component reliability, operation & maintenance, and use of the system. The main causes of the failures have been uneducated and unexperienced contractors, operators and users. The maintenance of the system have been poor and the system have been misused and vandalized. In addition, the system was not adapted to the local conditions. Table 32 presents the main failures in the main components of the vacuum sewer systems in Ondangwa and four other LA's in Namibia. In addition, it is listed the causes and impacts of the failures and suggested solutions.

Lack of component reliability also caused part of the failures. However, it was difficult to analyze what portion of the failures was caused by the lack of component reliability and what was caused by the users, poor maintenance, poor design or poor installation. Due to poor installation and improper material use, some of the pipe leakages must be caused by the lack of component reliability. In addition, the interface valve controllers are rather sensitive to the moisture and the collection chambers were not designed for the storm water.

Table 32. *Main findings of the study. The main failures, causes of the failure, impacts of the failures and solutions for the failures. * = in case of power outage.*

Component	Main Failure	Possible Cause	Possible Impact	Solution
Vacuum Station				
Vacuum Pumps	Continuous running	Poor maintenance Leakages	The systems does not function Low vacuum Flooding of collection chambers	Improve Maintenance Fix the leakages
Vacuum Pumps	Broken	Poor maintenance	Low vacuum Flooding of collection chambers	Improve Maintenance
Stand-by Generator	Not installed Broken	Poor maintenance installation and design	* The system does not function No vacuum Flooding of collection chambers	Installation of stand-by generator Improve maintenance
Vacuum Sewerline				
Vacuum Sewers	Leakages	Poor installation Sun light Excavation Poor maintenance	Low vacuum Vacuum pumps overworking Chambers flooding	Improve maintenance Fix the leakages Mark the pipes
Vacuum Sewers	Blockages	Vandalism Misuse	Low vacuum (upstream) Flooding chambers (up-stream)	Improve Maintenance Open the blockages User education Collection chamber protection

Collection Chambers				
Collection Chamber Piping/ Interface Valve	Blockages	Vandalism Misuse	Flooding of the blocked chamber	Improve maintenance User education Collection chamber protection
Interface Valve	Malfunctioning Stuck open or closed	Misuse Vandalism Strom water Lack of spare parts	Flooding of the malfunctioning chamber Low vacuum	Improve maintenance User education Collection chamber protection Spare part plan

The failures of the vacuum sewer systems in Gobabis, Henties Bay, Kalkrand and Stampriet have been very similar with the failures of the vacuum sewer system in Ondangwa. In addition, the main causes of the failures have been very similar. However, the system in Henties Bay had the least amount of failures and the vacuum sewer system in Ondangwa had the biggest amount of failures. In Ondangwa the system did not operate anymore.

The results of this thesis are rather unexpected. It was known that the vacuum sewer systems are malfunctioning and having failures. However, the scale of the failures was bigger than expected. The failures also covered more fields (design, installation, maintenance, user and component reliability) than expected.

The findings of this thesis are useful for improving the poor sanitation situation in Ondangwa and in the four other LA's. It is critical to get the vacuum sewer systems to operate properly and safely to decrease the negative impacts. In addition, the results of this thesis can be used on other vacuum sewer system cases in developing regions (and also outside the developing regions), to improve the situation and to prevent similar failures. Also in case the vacuum sewer system of Ondangwa is replaced by another sewer system this study gives knowledge how to prevent similar failures with the new system.

6.1.1 Vacuum Station

The main failures in the vacuum stations in Ondangwa and in the other LA's in Namibia have been the vacuum pumps and the lack of stand-by generators. The operation of the vacuum pumps and stand-by generator is critical for the functioning of the system. If the vacuum pumps do not operate, the entire system does not operate. In addition, in case of power failure, if the stand-by generator does not operate, the entire system does not operate. Malfunctioning of the vacuum pumps or the stand-by generators in case of power failure result in flooding of the collection chambers and expose the operators and users on health risks.

The main cause for the failures with the vacuum pumps have been poor maintenance and leakages in the system that cause continuous running of the pumps. In addition, due to the leakages the vacuum pumps do not reach the turn off level vacuum. The cause of stand-by generator failures have been the lack of stand-by generator or there is no skill to maintain the generator.

To improve the situation the key is to improve the overall maintenance. To train the maintenance personnel and to make the maintenance more organized is essential. Fixing the vacuum sewer leakages and protection of the vacuum sewers by marking them is also essential. In addition, maintenance or installation of stand-by generators are critical because in Ondangwa and other LA's of Namibia it occurs frequently power failure.

6.1.2 Vacuum Sewer Lines

The main failures in the vacuum sewer lines in Ondangwa and in the other LA's in Namibia have been leakages and blockages. In addition, the improper installation of the pipelines causes failures on the functioning of the system in some of the LA's. Leakages cause poor vacuum build-up in the sewers and that results in flooding of the collection chambers and exposes users and operators on the health risks. In addition, also blockages result in flooding of the collection chambers up-stream from the blockage and exposes users and operators on health risks. Flooding of the collection chambers can also cause groundwater and soil contamination.

The main cause for the leakages is typically poor installation including improper material use, excavation of other services in the same trench and the UV of sunlight in open trenches. The maintenance personnel in Ondangwa and other LA's lack skills and tools for spotting the leakages. Therefore the duration of the failure becomes longer.

The main cause for the blockages of the vacuum sewers have been mainly the users. Too big obstacles have been flushed through the toilet pans and thrown directly into the collection sumps. The collection chambers are not protected against vandalism and the users are not educated to use the system. The maintenance personnel in Ondangwa and other LA's lack skills and tools for spotting the blockages. Therefore the duration of the failure becomes longer.

To improve the situation the key is to improve the overall maintenance, provide user education and protect the system. To train the maintenance personnel and to provide required tools are essential for fixing the failure properly and fast. The amount of blockages can be decreased by decreasing vandalism and misuse of the system by user education. Also protection of the collection chambers decreases the impacts of vandalism and marking of the vacuum sewers decreases damage done while excavating other utilities in the same trench. Collection chambers can be protected by locking them. In addition, the whole network need to be observed to find all the blockages and leakages of the network. It is crucial to open the existing blockages, fix the leakages and the parts of the sewer line that are not installed properly.

6.1.3 Collection Chambers

The main failures in the collection chambers in Ondangwa and in other LA's in Namibia have been the malfunctioning of the valve controllers and blockages in the chambers. Malfunctioning of the interface valve or valve controller typically either results in continuously open or closed valve. This causes overflowing of the collection chamber where the valve or valve controller is located and exposes the users and operators on health risks. The overflowing of collection chamber also result in broken valve controller, because the controllers are sensitive to moisture.

The main cause for the failures with the collection chambers have been vandalism, storm water and lack of spare parts in Ondangwa and in other LA's. In addition, component defect is also a reason for the collection chamber failures. Especially the controllers are sensitive to moisture and fail easily. Also failures in other components of the vacuum sewer systems have also lead to overflowing of collection chambers. These failures are leakages or blockages in the sewers or malfunctioning vacuum pumps. Vandalism have cause failures to the collection chambers by blocking the system. Too big obstacles have been flush through the toilet pans or thrown directly into the collection sumps. The collection chambers are not protected against vandalism and the users are not educated to use the system. In addition, lack of spare parts prolongs the failures with broken interface valves. Spare parts are expensive and the delivery takes 6 months.

To improve the situation the key is to improve the overall maintenance, to provide user education, protect the system and make a spare part plan. To train the maintenance personnel, to provide required tools and to have spare parts always in stock are essential for fixing the failure properly and fast. In addition, user education is critical for decreasing the amount of vandalism and misuse that leads to the collection chamber blockages. Also protection of the collection chambers decreases the impacts of vandalism. Collection chambers can be protected by locking them. In addition, fixing all the malfunctioning chambers and fixing other components (sewers, vacuum pumps) that leads to overflowing of the collection chambers is crucial. The impacts of storm water can be avoided by flood-proof model of collection chambers. In addition, bigger interface valve diameter could improve the situation.

6.1.4 Maintenance

The main failures with the maintenance have been insufficient maintenance. The vacuum sewer systems have lacked proper maintenance, resulting in broken components or prolonged failures in the system. Typically vacuum pumps have broken down due to lack of maintenance and the operators have found difficult to spot and fix the leakages and blockages due to lack of skill, tools and spare parts. The poor maintenance have been often a cause of the failures of the major component of the systems in Ondangwa and other LA's in Namibia. One failure leads to another failure because vacuum sewer system is a system where one component is in interaction with other components.

The main cause for the poor maintenance have been lack of capacity, skills, tools, spare parts, documentation and schedule. The insufficient budgets of the Councils results in lack of maintenance capacity. There is not enough budget to hire enough labor force or to train the operators. In addition, the lack of budget affects on the lack of proper maintenance tools and lack of spare parts. The spare parts are not locally available, the delivery takes 6 months. In addition, the stage of maintenance have been emergency maintenance continuously in all the LA's. The maintenance personnel do not have capacity to carry out emergency maintenance continuously.

To improve the situation it would be essential to provide comprehensive training to the maintenance personnel of Ondangwa and other LA's. The training should include technical knowledge about the system, but also how to manage, document and schedule the maintenance. In addition, it would be essential to provide appropriate maintenance tools and have spare parts available always. The spare part situation can be improved by making a plan and having always certain amount of certain spare parts in the stock. These acts would decrease the time used for fixing the failures, avoid system from collapsing and avoid operators and user from being exposed on health risks. In addition, it is essential to fix the main failures of the vacuum sewer system, and to decrease vandalism to get in the stage of normal and preventative maintenance.

6.1.5 Users and Vandalism

The main failures caused by the users in Ondangwa and in other LA's in Namibia have been the misuse of the system and vandalism. People have flushed too big obstacles trough the toilet pans or they have thrown solids straight to the collection chamber sumps. In addition, they have broken down some visible component of the system. The main cause for the misuse and vandalism have been lack of user education and the lack of system protection against vandalism. The users have not been educated in the LA's and the chambers are not locked.

To improve the situation it is essential to provide user education and protect the system. Covering the vacuum chambers by metal covers and locking them is essential. This way people do not have access to throw foreign obstacles to the system through the chambers. The amount of chamber blockages and pipe line blockages will be reduced. Also number of broken chambers will decrease. In addition, acts such as providing playgrounds for the kids, waste separation at source, feedback system and provision of toilet papers could decrease the amount of failures caused by the users.

6.2 Inadequacies of the Study

This study has also some limitations. During the field trip in Namibia it was not available proper tools (such as pipe camera) to make more detailed analysis on the condition of the vacuum sewer system. In addition, due to the malfunctioning vacuum pumps it was impossible to conduct troubleshooting on the vacuum sewer system. The possible leakages and blockages of the system are not spotted.

Some people related to the vacuum sewer system in Ondangwa were not willing to tell essential information of the system, and sometimes the information regarding the vacuum sewer system was contradictory. In addition, the archives of the Ondangwa Town Council were incomplete. Some important documents were missing, such as as-built drawings of the system. In other LA's the available time was too short to make more detailed observations.

7. CONCLUSION

The purpose of this thesis was to analyze the malfunctioning vacuum sewer system in Ondangwa, Namibia. The system did not form adequate vacuum to transport sewage from the formation place to the vacuum station and therefore the collection chambers were flooding. The aim was to find the failures that cause the malfunctioning, causes of the failures and solutions for the failures of the vacuum sewer system in Ondangwa. In addition, failures in four other vacuum sewer systems in Namibia were studied for comparison purpose. The systems were located in Gobabis, Henties Bay, Kalkrand and Stampriet. A two month field trip was done in Namibia in October and November 2014 and three methods were used to analyze the vacuum sewer systems. The methods were literature survey, semi-structured interview and observation.

According to the analysis done for this thesis it was found that the vacuum sewer system in Ondangwa has faced many failures since the beginning of the design phase in 2006 until November 2014. All the four vacuum pumps were broken, vacuum sewers were leaking and blocked, part of the collection chambers were blocked and part of the interface valves were stuck open or closed position in November 2014. There had been also issues during the construction and design phases: improper land surveys and laying of the pipes.

Majority of the failures have been caused by external factors (vandalism, misuse of the system and poor maintenance) and local conditions. However, the system have been also difficult to maintain in the local conditions. The operators lacked skills, training, special tools and spare parts. The users were not educated, they flushed and threw too big obstacles to the collection chamber sumps. Material defect has also caused failures: the valve controllers break down easily when they are in touch with moisture and storm water have been able to enter the system. The impacts of the failures have exposed users and operators of the system on the health risks due to the sewage on the streets. In addition, the environment is exposed on contamination.

The main failures of vacuum sewer systems in Gobabis, Henties Bay, Kalkrand and Stampriet have been similar compared to the failures in Ondangwa: vacuum pump failures, leakages and blockages in the vacuum sewers, blockages in the collection sumps and interface valve failures. In addition, the main causes of the failures have also been similar: vandalism, misuse of the system, poor maintenance and material defect. The system in Henties Bay had the least amount of failures and the system in Ondangwa had the biggest amount of failures. The system in Ondangwa did not operate anymore due to the four broken vacuum pumps in November 2014.

In developed regions the vacuum sewer systems have had less failures than in Namibia. Therefore the conclusion is that the issue has been the adaptation of the system to the local challenging conditions, rather than a defective technology. A vacuum sewer system needs to be integrated in the environment where it is installed. Another conclusion is that the vacuum sewer system is more suitable in developed regions than in developing regions.

Ondangwa and the four other LA's of Namibia have two options. They should either invest on the improvement of the vacuum sewer systems or replace them with more applicable sewer systems. To improve the operation of vacuum sewer system, the system must be well investigated to find out all the existing critical failures. The failures must be fixed with proper materials and by proper contractors. In addition, the systems must be better protected against vandalism, traffic and weather conditions. In any case it is essential to improve the maintenance of the system, educate the users and protect the system against vandalism. Otherwise vandalism and inadequate maintenance will cause failures also in the future, no matter what system is operating.

However, this study only focuses on the improvements of the existing vacuum sewer system. Due to the numerous failures with the vacuum sewer system in Ondangwa, the better solution might be replacing the system with another sewer system to improve the poor sanitation situation. This study does not take into account the economical aspect. The costs of the suggested improvements are not known. The future research regarding the sanitation situation in Ondangwa could try to find out the most suitable solution for the poor sanitation situation from the environmental, financial and technical aspects. In addition, it is critical to take into account the local conditions and external factors that have caused failures with the vacuum sewer system.

The findings of this thesis are useful for improving the poor sanitation situation in Ondangwa and in the four other LA's. It is critical to get the vacuum sewer systems to operate properly and safely to decrease the negative impacts. In addition, the results of this thesis can be used on other vacuum sewer system cases in developing regions (and also outside the developing regions), to improve the situation and to prevent from getting similar failures. Also in case the vacuum sewer system of Ondangwa is replaced by another sewer system this study gives knowledge how to prevent similar failures with the new system.

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