UNDERSTANDING SEWAGE PUMP STATIONS

Development of a SEWPUMP Tool

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TT 627/15

WATER RESEARCH COMMISSION

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Report to the
WATER RESEARCH COMMISSION

by

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on behalf of
Stellenbosch University
Institute for Water and Environmental Engineering

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The publication of this report emanates from a project entitled *Sewer pump stations and related problems* (WRC Project No K5/2007/3).

This project consists of the following products:
1. Understanding Sewage Pump Stations (this report)
2. SEWPUMP Tool (available on the enclosed CD)

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EXECUTIVE SUMMARY

Scope of the study

Pumps are essential components in most sewer systems and are often considered by operators and managers to be the most problematic. The project sets out to address a number of pertinent issues with regards to sewage pumps, pump stations, and related elements of sewer systems.

South African sewer systems and storm drainage systems are designed as separate systems. The sewer is traditionally waterborne. Waterborne sewers (also called conventional sewers) use water as the mode of transport for excrement and other waste. This research project focused exclusively on separate waterborne sewers and specifically on decentralised sewerage pumps and related infrastructure in the piped sewer system; wastewater treatment and pumps used in the treatment process are thus excluded per definition.

The issue at hand extends beyond hydraulics and design criteria to enable stakeholders to decision support and communication. The aim was to link decisions to problems occurring at sewage pump stations during normal operating life, after commissioning. One of the key issues addressed by this research and the subsequent software tool revolves around improved knowledge transfer and communication between different levels of technical staff involved with sewerage pumps.

Motivation

This project was motivated by the general lack of published research into sewer pump stations and related problems, combined with the need for such knowledge during the planning, modelling, optimisation, design, operations and maintenance phases of these infrastructure elements. A recent WRC project culminated in a design guideline for waterborne sanitation (Van Vuuren and Van Dijk, 2011a) as well as a guideline addressing operation and maintenance of these systems (Van Vuuren and Van Dijk, 2011b). One of the outcomes of the former project was a product called SewerAID – a DVD providing background on various matters pertaining to waterborne sewers as a whole. Findings from their studies pointed to critical research needs with regards to sewer pump stations and related problems.

Subsequent to the work by Van Vuuren and Van Dijk (2011a; 2011b), a need remained to assess various aspects relating to sewerage pumps and related problems in more detail, backed by data from the field. A lot of experience over the years has been gained based on practical considerations, particularly as it pertains to local conditions and the eventual problems that have been "solved on-site" by operators and technical staff responsible for operating sewerage pumps. This research project also allowed for the review, capture and dissemination of such knowledge.

Key objectives

The key objectives of this study were to:

- Conduct a knowledge review of sewage and -pumps
- Select or derive a classification system for sewerage pumps and related problems
- Conduct field work and data collection to determine the types of problems typically experienced during the operation of sewerage pumps and the possible causes and to better understand these problems
- Analyse the field data in order to extract useful information

- Develop a practical software tool intended as a training and communication tool regarding pump station problems
- Report a select portion of the research by means of a peer reviewed journal article
- Report on all the above knowledge and findings as the final deliverable report.

The list above provided direction and actions required to address these issues were the main drivers of the project.

Sewage and solids

Sewers operate over a wide range of flow rates and the limiting values need to be taken into account when evaluating how effectively a sewer will transport solids to a pump station. Effluent velocity at the various flow rates is the most significant factor influencing the transport of solids through a sewer.

The content and relative contribution of solids type to the total solids varies from one catchment to another and is influenced by the flow rate in various ways. The solid load by mass for industrialised countries has been reported to vary between 100 mg/l and 500 mg/l for sanitary solids and between 50 mg/l and 1000 mg/l for storm water solids (Ackers et al., 1996). Czarnota (2008) reminds that, although the concentration of solids mass per volume of water may appear to be low, the gross quantity of solids passing through the system may be significant. The total solids mass is proportional to the sewage flow rate.

A distinction needs to be made between the solids that can be transported through a sewer in terms of their specific gravity relative to that of the effluent, whether or not they will disintegrate with time and their impact on the operation and life of pumps. As the clogging of pumps by material that had a specific gravity similar to that of the effluent was a problem and little literature on the subject could be found, a series of laboratory experiments was done to determine the effectiveness of screening baskets in removing these materials. Recommendations for the location of screening baskets relative the effluent levels in the sump where they are to be placed were made and the need for further research in this regard was noted.

Problems and causes

Identifying, listing and classifying the problems and how the measurement of the intensity or extent would be quantified was a particular challenge faced by the research team. The term “problem” is used loosely in this research project. A clear distinction needs to be drawn between problems and their causes. If the underlying causes are not identified and addressed, the problems will keep occurring. This study could be considered as one addressing problems (direct) versus the underlying causes (indirect). The effort at addressing the problem at a sewer pump could be distracted from its focus by tracing the problem back to the underlying cause. These underlying causes may have to be considered as the actual issue to be addressed. However, the emphasis here was to address particular problems relating to pump stations in the most direct way possible at the pump stations.

During the problem identification phase of the project it became apparent that boundaries had to be established to prevent the proliferation of problems and their causes that were beyond the scope of the study. A problem was therefore limited to an issue that could be determined by means of inspection at the pump station site, discussion with the operation and maintenance staff, or by reviewing documentation covering problems.

A comprehensive list of common problems was compiled from literature, site visits and stakeholder interviews during this research. The listing by Van der Merwe-Botha and Manus (2011) and Sidwick (1984) of some common problems relating to sewers and pumps is the only local peer reviewed report of this nature that could be found during the knowledge review. In this study problems at sewage pump stations were identified following an in depth literature study in conjunction with a combination of field visits and stakeholders interviews at selected sites in the Western Cape, Gauteng and KwaZulu-Natal.

Sewer pump station problems were ultimately categorized into four classes. Each direct problem identified in the first phase of the project could ultimately be placed into one (or more) of these four problem classes, based on a degree of membership to each class. In presenting the framework here, aspects regarding roles and responsibilities were not included, so as to maintain the focus. These would be an obvious future extension to the framework presented here. The four classes ultimately arrived at were coined the 4 O's of sewage pump station problems, namely: overflows, odours, operational (and maintenance), other. These four classes were described by explanatory tree diagrams and formed the basis for the items listed in the SewPump tool.

Stakeholder workshop

The Water Institute of Southern Africa (WISA) held its biennial conference at the Cape Town International Convention Centre from 6-10 May 2012. WISA2012 was considered the ideal venue to workshop queries regarding sewer pump problems and the tools forming part of this project. Workshop 22 entitled "WRC – Practical application of research: A Tool for sewer pump problems" was hosted by the project team at the WISA2012 conference as part of the formal conference programme.

A total of 28 delegates actively attended the workshop, with more than a third of them being from a few large municipalities, including mainly Ekurhuleni Metro Municipality and the City of Cape Town. Most of the feedback gained came from the Ekurhuleni staff. Two notable groups of delegates who also actively took part in the discussions were from engineering consultants and students. The approach was to gain an in-depth understanding of the participants' views regarding sewer pump problems and the software tool. The delegates discussed various aspects of sewer pump problems, pump stations, and the intended tools being developed as part of this study. The feedback from the workshop was incorporated to the final development of SewPump.

SewPump Tool

The name SewPump tool was derived from "sew..." (sew: mend or repair...; arrange something in an acceptable way); and "sew..." being the three leftmost characters in the word "sewer". SewPump was aimed at providing information regarding sewer pump problems. The tool was developed to act as a visual aid for staff involved with the operation and management of sewage pump stations, thus providing useful information in a structured and convenient way. The aim was to keep the tool uncomplicated with limited inputs and maximum output.

It was clear that, with clever planning, SewPump could also be used to cut through communication barriers between different staff levels and it was extended to address that need. It was noted during site visits that there was a need to address communication between pump station operators and their respective managers. The same was reported during the WISA2012 workshop. The research team set out to develop a tool that would address the concerns and needs (based on feedback) coupled with a method of communication between operators and technical management.

A software developer was employed to develop an html-based stand-alone software tool with the following three main focus areas:

- Identification: Help to understand and identify problems at sewer pump stations
- Communication: Facilitate communication between pump station operators and management
- Training: Should transform to a training tool that could be used by individuals for self-study and by managers to facilitate training.
-

The SewPump Tool is saved on a CD and attached to this report

Conclusion

Two aspects need to be understood when referring to sewage pumping, namely the pump station (infrastructure and equipment) and the sewage stream to be pumped. This research project included a review of both these aspects. It was concluded that both were well documented, based on former research. However, previous publications regarding solids in sewers and their behaviour were limited, particularly with regards to baskets that were found to be very common in local sewage pump installations. Limited laboratory tests were conducted to investigate the interaction between solids in sewage and screening baskets.

This project entailed numerous site visits to sewage pump stations, aimed at gaining information from the field and learning about the practical matters pertaining to the daily operation of sewage pump stations as well as related problems. A workshop was organised at the WISA2012 conference, where feedback was gained from the delegates regarding sewage pumping and the proposed tools developed by the project team. The team concluded that operators and managers alike see sewage pumping as a problem; one of the key concerns noted during the site visits and the workshop was the poor communication between technical managers and operators.

A tool was developed as part of this project that would: (i) aid operators with sewage pump problem identification so as to help understand and identify problems at sewer pump stations, (ii) facilitate communication between pump station operators and technical management, and (iii) provide for basic training regarding sewage pumping and related problems that could be used by individuals for self-study and by managers to facilitate training.

The outcomes of this project would aid a Municipality and their engineering consultants to better understand the working of a sewerage pump station and the related problems. The expectation of a maintenance free sewage pump station should be replaced by empowerment.

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The Reference Group responsible for this project consisted of the following persons:

Dr V Naidoo	Water Research Commission (Chair)
Prof NP Armitage	University of Cape Town
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Mr JL Harrison	eThekwini Water and Sanitation
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Mr Gweraga Dambudzo	Johannesburg Water (Pty) Ltd

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ABBREVIATIONS AND ACCRONYMS

AADD	-	Average annual daily (water) demand
ADWF	-	Average dry weather flow
CSIR	-	Council for Scientific and Industrial Research
CSS	-	Combined sewer systems
d	-	day
DB	-	Drainage basin
DSS	-	Decision support system
du	-	dwelling unit (the equivalent term “stand” is also used in literature)
DWF	-	Dry weather flow
GIS	-	Geographic information system
IDP	-	Integrated development plan
IMESA	-	Institute of Municipal Engineering of South Africa
IMQS	-	A commercial software product (www.imqs.co.za)
JHB	-	Johannesburg
KSA	-	Key strategic area (WRC)
KZN	-	KwaZulu-Natal
LA	-	Local authority
LCA	-	Life cycle analysis
LCC	-	Life cycle cost
NPSH	-	Net positive suction head
N_s	-	Specific speed
O&M	-	Operations and maintenance
PAT	-	Pump station Analysis Tool
PDWF	-	Peak dry weather flow
PS	-	Pump Station
PVC	-	Polyvinyl Chloride
PWWF	-	Peak wet weather flow
RG	-	Reference group (relating to the WRC project)
SABS	-	South African Bureau of Standards
SDF	-	Spatial development framework
SEWSAN	-	A commercial software product (www.gls.co.za)
SHD	-	Solids handling device
SPS	-	Sewage Pump Station
SSS	-	Separate sewer systems
SU	-	Stellenbosch University
TOR	-	Terms of reference
UJ	-	University of Johannesburg
uPVC	-	Unplasticized Polyvinyl Chloride
VSD	-	Variable speed drive (pumps)
WRC	-	Water Research Commission
WSDP	-	Water services development plan
WWTP	-	Wastewater Treatment Plant
WWTW	-	Wastewater treatment works
$\lambda(t)$	-	Hazard rate (failure rate) as function of time

1. INTRODUCTION

1.1 Background

Pumps are essential components in most sewer systems and are often considered by operators and managers to be the most problematic. The project sets out to address a number of pertinent issues with regards to pumps, pump stations, and related elements of sewer systems. This comprehensive technical report is aimed at academic readership and may also be useful as an aid to technical managers involved with sewer pumps or related problems. A practical booklet was also produced as part of this report, aimed at operators.

1.2 Motivation

This project was motivated by the general lack of published research into sewer pump stations and related problems, combined with the need for such knowledge during the planning, modelling, optimisation, design, operations and maintenance phases of these infrastructure elements. The issue at hand extends beyond simplistic hydraulics and design criteria to enable stakeholders to link design concepts at an early stage to problems occurring at sewage pump stations during normal operating life, after commissioning. One of the key issues addressed by this research and the subsequent software tool revolves around improved communication between different levels of technical staff involved with sewer pumps, and basic training of operator-level staff.

The need for pumping sewage arises frequently. Steel (1960) lists a few specific conditions where the pumping of sewage is necessary. These include:

- where the sewage needs to be conveyed over the top of a ridge, or similarly elevated area, as dictated by the topology of the area and layout requirements of the sewer system
- where topography results in relatively deep gravity sewers, or otherwise expensive excavations (including excavation in rock) where pumping facilities could provide cheaper solutions
- where basements of buildings are lower than the connection to the sewer system
- where the sewer system outlet is below the receiving body of water so that it is necessary to raise the sewage to gain sufficient head for gravity feed through a WWTW.

In a former study by De Swardt and Barta (2008) a first order national audit of sewerage reticulation issues was presented. In that study various aspects pertaining to sewer infrastructure were identified as potential and urgent future research projects. This research project has its origin in these formerly identified areas of need. These areas of need identified earlier are briefly outlined below, with the specific reference to the item numbers in the report by De Swardt and Barta (ibid.) given in brackets:

- Establish standard requirements for pumping installations in municipal waterborne sewer systems. (Item A.6.2 – Hydraulic, Structural and Prediction Models)
- Standards and guidelines for design of sewer rising mains (A.6.4 – Design)

- Design guidelines for continuous wastewater pumping from the wet or dry well (A.6.4 – Design)

- Evaluate reliable in-line flow monitoring techniques (A.6.8 – Inspection and Monitoring)

- Investigate miniaturized sensors and wireless data transmission (A.6.8 – Inspection and Monitoring)

- Investigate remote sensing and modern monitoring devices (A.6.8 – Inspection and Monitoring)

- Guidelines for the design and operation of sewer pump stations in separate sewer systems (A.6.14 – Sewer Appurtenances).

In addition to the above some specific possible research projects were identified in the study pertaining to the issues on sewer pump stations and rising mains. The following needs were presented by De Swardt (ibid.) and culminated in the original research proposal for this project.

- Guidelines for the operations and maintenance of sewer pumps stations: There is often a divide between theoretical designs of pump stations by engineers and the practical operation and maintenance of these pump stations by local authorities. Research and produce a practical tool giving tips on pump station design and operation, as well as facilitating the flow of information between different levels of management.

- Revision of established standards for gravity sewers, sewer rising mains, pump stations and specific sewer structures: Research, evaluate and propose revisions to established standards and existing guidelines for gravity sewer, sewer rising mains, pumping stations, sewer tunnels and special structures.

The latter point was covered to a certain extent by a recent WRC project culminating in a design guideline for waterborne sanitation systems (Van Dijk et al., 2010). Findings from the study pointed to critical research needs with regards to sewer pump stations, rising mains, siphons and methods for removing insoluble matter. This document includes valuable and substantial information on sewage pumps, much of which is referred to in this document for completeness. This study incorporated some aspects of design guidelines pertaining to sewer pumps and pump stations.

Subsequent to the work by Van Dijk et al. (2010) a need remained to assess various aspects relating to pumped flow and related problems in more detail, backed by data from the field. These items included: pump stations; rising mains; methods for handling insoluble matter at these installations. Particular concerns were also raised by some stakeholders from local authorities during a previous project into sewer system planning (Jacobs et al., 2011) as to the need for a decision support tools to select appropriate pump technology and guide operators.

The question arises as to why these "pressure" elements justify further research above gravity sewers that comprise by far the greater share of a typical sewer system in terms of asset value and sheer length of pipe in the ground.

Firstly, pump stations require energy input – in contrast to gravity sewers where flow is induced by gravitational forces. This alone brings added costs and complexity when modelling pump-pipe systems. Secondly, from a strategic point of view sewer pump stations form only another component of the entire sewer system. Rising mains are another, and are often separately assessed. However, as these two components are integrated hydraulically they should be optimised in combination, not separately (Atkinson et al., 2000). This is true for both water and sewer systems.

Balancing the components of sewer systems adds complexity and publications on the topic to date are limited. An example of the typical design problem an engineer could have to address is whether to provide a large pump and a relatively smaller diameter rising main, which would require more power than the alternative of providing a smaller pump and larger diameter rising main. These components thus require special attention in providing an optimal design. Hydraulics and theory have their place, but a lot of experience over the years has been gained based on practical considerations, particularly as it pertains to local conditions and the eventual problems that have be solved "on-site". This research project also sets out to assess and address these in-house solutions to site-specific problems.

1.3 Objectives of this study

1.3.1 Broad aims

The key component to this project was to provide a useful aid to those in the engineering fraternity responsible for designing, planning operating and maintaining sewer pump installations. Published research is seen as one avenue to disseminate knowledge under peers, with results filtering into lecturing notes. In addition this study intended capturing as much local knowledge in this field as it could, and presents a solution in the form of a software tool for use by operators, planners, managers, engineers and academics.

In the execution of this research the project output could have been steered to suit those with a viewpoint of designing new pump stations, versus maintaining existing ones. Subsequent to stakeholder input during the progress of this project the focus of the research shifted towards existing pump stations – and ways of assisting operators involved with related tasks to maintain them. An underlying aim was to structure the deliverables in such a way that it would also aid those involved with the design of new pump stations.

1.3.2 Target stage of project

Prior to listing the key objectives some attention should be paid to the particular stage of the design life intended as the focus for this research. The key driver behind this work is the reduction of any type of problem experienced with sewer pumps, by improving the design of key elements in existing and new pump stations. The target stage is best described by considering the typical "bathtub curve", shown in Figure 1-1, applicable to engineering reliability problems. This curve is also often called the hazard function of a system or component.

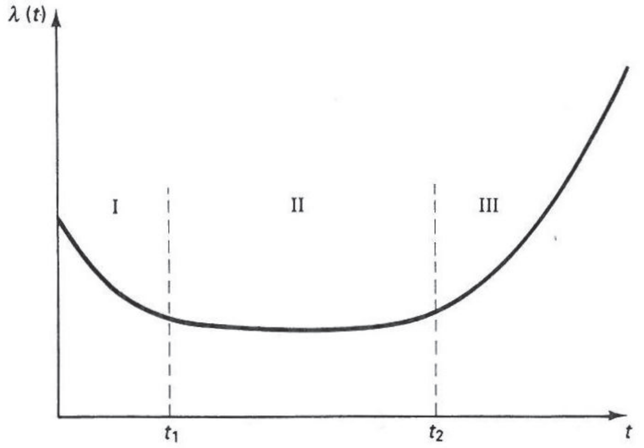


Figure 1-1. Typical bathtub curve or hazard function (Ramakumar, 1993)

The curve shows three distinct stages of time in the typical life of any engineering system, depicted by the regions I, II and III, moving from left to right as time progresses. The y-axis represents the hazard function, λ, as a function of time (t). An increased value for λ describes an increased failure rate (thus an increased "number of problems"):

- A relatively high prevalence of problems is expected in the early stages of the active system life, shortly after commissioning. This high problem frequency pertains to those problems resulting from poor design, incorrect construction, manufacturer's defects, and the like. After the system has been "run in" these problems would have been corrected or mitigated in some way so as to arrive at the second and predominant phase of the system life.

- The horizontal part of the curve between t_1 and t_2 pertains to the normal operating life of the system, with relatively few problems. Sewer pump stations are known to have a relatively high failure rate, even during this normal operating life, this complicating the identification of the shift from region II to region III.

- When the system reaches the end of its intended design life at t_2 the hazard rate λ (t) that describes the frequency of problems, increases due to system failure. The failure rate in this phase is normally relatively high compared to the normal operating life of the system and the failure of components would increase with time to an unacceptably high level when it would become necessary to replace the system, or the problematic components thereof.

In essence this project output is expected to lead to "improved reliability" of local sewer pump stations in years to come with a focus on the normal operating life. The hazard function reminds us that two other phases are also applicable and should be addressed along with the normal operating life. South Africa has been noted to have ageing infrastructure and requires special attention to the final phase. The focus of this study is to reduce the failure rate of pumped sewer systems and their components during their relatively long normal operating life.

1.3.3 Key objectives

The key objectives of this study, as defined in the proposal initially submitted to the WRC, centre on the following:

- Conduct a knowledge review
- Select or derive a classification system for sewerage pumps and pump stations, related infrastructure as well as reported problems
- Conduct field work and data collection to determine the types of problems typically experienced during the operation of sewerage pumps and the possible causes and to better understand these problems.
- Analyse the field data in order to extract useful information.
- Develop a practical pump-pipe design model (software tool) intended as a training and communication tool regarding pump station problems.
- Report a select portion of the research by means of a peer reviewed journal article.
- Report on all the above knowledge and findings as the final deliverable(s).

The list above provided direction and actions required to address these issues were the main drivers of the project.

1.4 Definitions and terminology

1.4.1 Sewer pump

The most basic definition of a pump is a device used to move fluids, such as liquids, gases or slurries (Wikipedia, 2010). A pump displaces a volume by physical or mechanical action. Pumps are classified into five major groups according to Fraenkel (1986), each describing the method for moving the fluid: direct lift, displacement, velocity, buoyancy and gravity pumps. This classification is also adopted by Wikipedia (2010) for the definition of the word "pump". Pumps are classified in different ways, with detailed descriptions of different classification systems available in the literature (Jones et al., 2008). In addition to centrifugal and propeller pumps, of which the former is by far the most common in wastewater systems, the following types of pumps have long since been noted (Fair et al., 1971) to be used for pumping sewage as well: displacement pumps, rotary pumps, hydraulic ram pumps, jet pumps, air lift pumps where air bubbles are introduced to induce upward flow and displacement ejectors. The focus of this study is on decentralised pump installations in the piped sewer system, rather than those at the WWTP.

1.4.2 Sewer pumping station

Pumping stations are defined by Wikipedia (2010) as facilities including pumps and equipment for pumping fluids from one place to another. They are used for a variety of infrastructure systems and include applications for the removal of sewage to processing sites.

1.4.3 Pump station problems

The most sensible way of quantifying these problems is by means of discussion with the reliable operation, in other words determining the system reliability from the person with the hands on experience. The term "problem" is used loosely in this report and it is not linked to reliability theory, despite the understanding that in a pure technical sense the definition would be linked to system reliability.

1.4.4 Other

General terms pertaining to sewer systems, such as sewer and sewerage along with many others, have been well defined by means of a mini-dictionary list presented by Jacobs et al. (2011).

1.5 Sewer system types

A combined sewer system is defined as a system where sanitary sewerage and stormwater runoff are handled in a single pipe system by design. This has an obvious effect on sewer overflows because of the large variance between dry and wet weather flows. It was implemented in the earlier days (early 20th century) and can therefore be found in older cities and towns overseas.

The purpose of a separate sewer system is to convey sanitary sewerage to a wastewater treatment works (WWTW). Separate sewers are also called sanitary sewers or foul sewers. Conventional sanitary sewer systems consist of a network of pipes that rely on gravity to convey the sewage to the WWTW. In this report the term "sewer" is used to describe a sanitary sewer.

Alternative types of sewers are available, but were not addressed in this study. Examples include vacuum and small-bore sewers. Small-bore sewers are also commonly known as solids-free sewers and are found in some parts of South Africa (Little, 2004). A solids-free sewers system is a system that disposes of the sewage, with the help of an on-site tank to settle solids out. In a small bore system the liquid only is conveyed into the sewer piping system (du Pisani, 1998). The solids remain in the tank where they are exposed to anaerobic bacteria and converted to carbon dioxide, ammonia, water and a residue, termed sludge (du Pisani, 1998). The volume of sludge builds up in the tank and must be removed at intervals, and transported to the WWTP, usually by vacuum tanker. With most small bore systems the inceptor tank (settling tank) is located on the user's property or very near the location of disposal. Therefore users need to have the knowledge of what items cannot be flushed and appreciate that if they do flush an object or product that could cause a problem, they that might end up with the problem on their property (Nel, 2011). This system puts the responsibility for reliability of the system in the user's hands.

One municipality involved in this study had a few solids-free sewers in place as sub-components of a larger conventional sewer system. Visits during later phases of this project to this site also included these pump installations. It was clear that the pump stations on the solids-free sewer systems were not affected by problems to the same extent as those on conventional sewers in other parts of the same Municipality's system.

1.6 Iterative development of SewPump tool

One of the characteristics of this project was that the output was developed iteratively based on incremental input. Feedback was gained from potential users on partly-completed conceptual software tools midway through the 3-year project. The research team set up two alternative software tools for this purpose to evaluate and probe the needs of potential users. These two alternative tools were evaluated in a workshop arranged at the WISA2012 Conference. By this time the knowledge review and field work had progressed and one tool was developed as the final software product. Additional input from the WRC project reference group at a critical point in the process (about the same time as the WISA2012 workshop) was considered invaluable in steering the team towards the desirable final product.

2. PUMP STATIONS AND PUMPS

2.1 Overview

2.1.1 Considering the need for pumps

Urban developments are often situated in such a way that the sewage cannot gravitate to the required collection point. In this case a pump station needs to be added to the sewer system. Operating costs for sewer pumps are often relatively high. Maintenance needs and the level of skill required for effective operation are also high, adding additional costs when pumps are involved. When a pump station is unavoidable the engineer should design it in such a way as to minimise the total cost of the pump station over its entire life cycle and should consider indirect costs incurred by problems that may occur during the life span of the pump station. Bloch and Budris (2004) however report that, despite the knowledge of better methods, most decisions regarding pump selection in the early stages of planning are still made solely on the basis of the minimum capital cost.

In agreement with the authors of this report and workshop feedback reported by Jacobs et al. (2011) as part of a study into sewer system planning, Van Dijk et al. (2010) suggest in a recent sewer design guideline that sewage pump stations should be avoided where possible and should only be considered where a gravity system to the existing sewer system is not feasible. Particular concerns were raised by some stakeholders during work by Jacobs et al. (2011) calling for the minimisation of the number of sewage pump stations during the design of new sewer systems to alleviate the numerous reported operations and maintenance problems associated with this infrastructure element.

Despite the desire by service delivery staff to rid sewer systems of all pumps, their presence in most systems remains inevitable.

2.1.2 Philosophy regarding solids and entrained matter

It is often argued that a notable number of sewage pump problems arise from the fact that the matter being pumped is not simply sewage – the pumps clog and are damaged by the passage of unwanted solids and entrained inorganic matter. Various reports have been provided over the years of unwanted matter being transported down sewers. The authors are personally aware of objects such as bricks, motor vehicle tyres, and even an old engine block that have clogged local sewers. Smaller items that are commonly found in local sewage include mealie-stalks, stockings, rags and the like that are used as cleaning medium in the place of toilet paper in some poor communities. A key question to ask in addressing pump problems is one on which local experts are divided: Should solids be removed at decentralised points such as all sewage pump stations, or should solids instead be conveyed along with sewage to the WWTW?

The two alternative philosophies involved imply different design approaches. The two extremes that could be considered are:

- Remove: remove all unwanted matter mechanically from the sewage (e.g. by means of traps, screens, baskets) at each pump station and discard it via road transport. This implies a decentralised approach to handling solids. Given the success of the method the pumps should handle only sewage and problems should theoretically be reduced. Sand traps upstream of pump sumps are an example of infrastructure intended to remove matter prior to pumping (Loubser, 2009).

- Convey: this approach advocates the transport of all matter, including solids, along with the sewage via pump stations to a final destination point at the WWTW, where it is finally removed as per WWTW-design prior to treatment. Solids removal is at a central location. Macerators are an example of infrastructure that could be used to disintegrate solid matter in order to convey it along the system with the sewage.

In most systems some middle way is implemented, whereby some solid matter is removed and some is conveyed. Rag traps and baskets are an example of items used to remove some matter prior to pumping. The two approaches differ notably in terms infrastructure needs and expected problems, so it would make sense for an entire system to be designed and operated with one of these philosophies in mind from the outset. Both of these approaches are far superior to allowing solids to collect in sections of the sewer where due to flat gradients or transitions the effluent velocity is not adequate to convey the solids through the sewer. Under these conditions blockages can occur at random along a sewer resulting in spillages in residential and commercial areas.

2.2 Design practice and criteria

2.2.1 Basic criteria and site selection

Sewage pump stations are normally located at the downstream end of the sewers draining sewage from a particular drainage basin (DB). Sewage pump stations have the reputation of being the scourge of the environment as they are notoriously prone to spillages, foul odours and other community health concerns. These undesired events normally occur at or near sewage pump stations due to poor operational procedures and the lack of maintenance, but could also be the result of poor design details built into the system.

This knowledge review addresses the practical aspects of site selection, pump station layout and the design of sewage pump stations. Improved decisions at the design stage could go a long way to reduce or alleviate pump problems and mitigate the risk of environmental pollution.

Van Dijk et al. (2010) list a few criteria that are to be met when selecting a pump station site and layout. The most notable criteria as adopted from this study are listed below:

- Pumps should be located to avoid gravity sewers being laid at depths of greater than 6 m

- Pump locations should be such that the associated rising main does not traverse private property and the rising main length is kept to a minimum

- The risk induced by a potential functional failure of the pump station or rising main should be minimised (there should be no possibility of a structural failure)

- The pump station should be located within a reserve of the local authority, a road reserve or on a property which is owned by the local authority for the intended life of the pumping station; the site must be accessible by vehicles by means of an all-weather road and the layout of the pumping station and other features must ensure that the available space for maintenance purposes is maximised

- Water and electricity supply should be available

- The pump station roof is to be constructed above the 1 in 100 year flood level and the top slab should be raised to at least 150 mm above the finished natural surface level; Van Dijk et al. (2010) note that some Municipalities use the 1:50 year flood level instead

- Minimise aesthetic issues and odour problems.

Selection of the pump station site is considered to be one of the key elements in reducing future problems. It may be possible to address some problems, after construction and commissioning, by redesigning and modifying certain elements of a pump station. However, once constructed it is usually impractical to modify the system details and surrounding gravity pipes to bypass the pump station or to dismantle or move the pump station completely.

2.2.2 Pump station design criteria

Both the University of Pretoria and Stellenbosch University present regular post graduate courses on water services that include sessions on pumping station design. From these notes a number of factors were identified that should be considered when designing a pressurised sewer pump station. It is necessary to establish the pumping requirements in terms of what needs to be pumped, the distance and elevation to which it needs to be pumped, the flow rate and other facilities that may be needed to make the pumping system work. The effects of possible breakdowns or malfunctioning on the surrounding area needs to be assessed. The environment should be taken into account by considering the type of structure/foundations, noise and odour levels. Despite this knowledge there is, to date, no user-friendly tool to aid designers in making these decisions.

In addition to the criteria presented above pertaining to the location of the pump station, Van Dijk et al. (2010) also lists criteria that relate to the design of the pump station per se. Many of the points are reinforced by other literature, but the list provided by these authors is compact and useful for inclusion in this knowledge review. The pump station should be designed so as to meet the following criteria:

- The design life of the pump station structure should be 100 years
- The design should strive to minimise long term maintenance and operation costs
- Pollution in the form of spillage, noise and odour, should be minimised
- The system control and warning alarms should be integrated with a telemetry system
- It should meet current environment protection guidelines and regulations
- Two complete pump sets and associated pipe work should be provided, with one duty and one on standby; both pump sets should be capable of operating simultaneously and both should be capable of pumping raw sewage
- Removal of equipment for regular maintenance and cleaning should be easy
- The sump should have sufficient storage capacity to prevent frequent on and off switching.

Some design criteria could be considered to be generic, while others could be site specific or driven by some other unique design requirements. The key is to get the crucial aspects right early on in the design process.

2.3 Typical pump station configurations

2.3.1 Traditional dual sump design approach – wet and dry wells

Various authors provide a detailed explanation of the traditional approach to designing sewage pumping stations (Brière, 1999; Butler and Davies, 2004; Steel, 1960). This section is adopted mainly from a recent publication by Van Dijk et al. (2010) that has a local origin in order to convey the key points. For further detail the reader could refer to these references.

The traditional approach to sewage pump station design incorporates both a so-called wet-well and a dry-well, as shown in Figure 2-1. The flow rate to be handled determines the typical design.

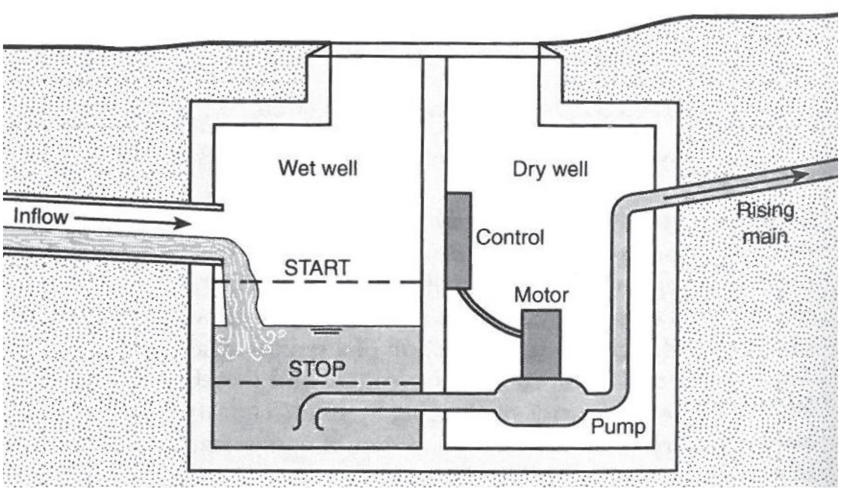


Figure 2-1. Typical conventional sewage pump station (Butler and Davies, 2004)

These two wells could even be designed as part of the same structure, thus simply being separated by an internal dividing wall. Pumps would be installed below ground level on the base of the dry well. The pump inlets would be below the high water level in the wet-well (sump) on pump start, thus ensuring that the pump is primed. Dry-wells are typically constructed underground although the mechanical equipment is isolated from the sewage in the wet-well.

The advantage of this design concept it that, in case of notable failure of the pumps or pipe work the sewerage could discharge directly into the dry-well, although Van Dijk et al. (2010) notes that complete flooding in such cases is not an uncommon occurrence. The electric motors are normally mounted above the emergency overflow and above the top water level of the wet-well. Thus, the motors, electrical switchgear and control electronics are usually located above ground level and drive the sewage pumps through a vertical shaft. Relatively small pump houses are needed to limit damage induced by weathering, vandalism and theft.

Local authorities often have in-house preferences for certain types of pump/s and impeller/s, but recent research (Van Dijk et al., 2010) suggests that a favourite choice in many local municipal guidelines is the horizontal, self-priming, centrifugal end-suction design (City of Tshwane Metropolitan Municipality, 2007).

The application of submersible pumps is often limited to special cases. Such pumps are typically applied in pump stations serving relatively small drainage basins of up to about 100 properties. This is in line with Brière (1999) who reports that a prefabricated unit may be used with a single well and submersible pumps for relatively small flows. Brière (1999) continues to state that for larger flows special pumping stations need to be designed that traditionally are equipped with a wet well for collecting wastewater and a dry well where the pumps and auxiliary equipment are installed. This Canadian publication is in line with local practice and criteria.

2.3.2 Sump well criteria

Sewer pump stations are often classified according to the relative placement of the pump and the sump (or well), often being classified as either a dry well or wet well setup. In actual fact the placement of the pump in the wet-well is simply termed a submersible pump. No matter where the pump is located, in all cases the wet-well is nothing more than the pump intake sump. The authors have noted some confusion in industry with the use of terms like "wet well pump station", when in fact all sewerage pump stations have a "wet well".

The design of the wet well is probably the most important part of the pump station in terms of design. Based on the experience in the project team it appears that the majority of operational problems are attributable to poor wet well design, or poor maintenance of crucial components in the wet-well system.

2.3.3 Basic types of installation

Figures 2-2, 2-3 and 2-4 depict the most basic alternate types of sewer pump installations in the form of simplified schematic sections.

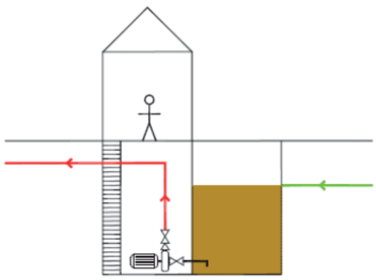


Figure 2-2. Schematic of a conventional dry well design

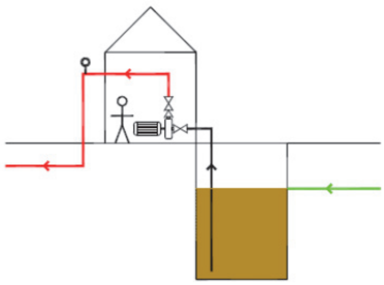


Figure 2-3. Schematic of a conventional dry well design with self-priming pumps

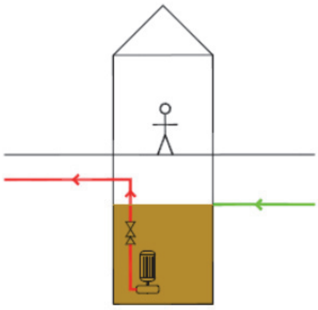


Figure 2-4. Schematic of a submersible pump station design

2.4 Pump station composition and associated infrastructure

2.4.1 Composition

A pump station site incorporates various components, all essential for the pump to be installed, maintained and operated effectively. According to Beaudesert Shire Council (2007) pumping station infrastructure includes pumps, electrical cabinet and wiring, pressure control, internal pipe work, telemetry control, housing and access, but mention is also made elsewhere in the same document of concrete benching in the wet well base, level control, internal pipe work and the well washer.

Van Dijk et al. (2010) also identified some critical components of a pump station facility that are perhaps in a way more practical in terms of engineering thinking. The components include: the building structure, electrical substation or transformer/s, access roads, the mechanical pumping equipment and other appurtenant equipment inside the pump station property. The facility design should also incorporate an access road and security measures (e.g. a fence, doors and locks, burglar bars), both of which may have a notable impact on problems experienced and maintenance operations at a pump station.

Each of these individual components, their selection and the numerous options for integration, result in a final pump station – one that will probably experience some problems at some future stage. The ideal selection of each component and the optimal combination into a single pumping station unit is not a matter of mere hydraulic calculations and application of straightforward design principles; it is a holistic approach which takes all the components into consideration.

2.4.2 Access and security

The facility design should incorporate an access road and security. The access road should provide passage for vehicles and personnel intended to maintain the pumping station as well as emergency vehicles that could be needed for example in times of power failures (for pumping sewage from the pump sump for removal by road), or blockages requiring vehicular-based repair (such as a “Jet Vac”). Security should be designed and maintained to keep unwanted persons out.

2.4.3 Aesthetics and graffiti

Some design guidelines for sewer infrastructure (e.g. Beaudesert Shire Council, 2007) specify that care should be taken to ensure pumping stations have an aesthetic appearance when located in a residential area. Also, local practice is that the architectural treatment should blend with the surrounding area and the pumping station should ideally be as aesthetically pleasing to the public eye as possible. Something as simple as effective paintwork, supported by the community, could reduce vandalism and improve public perception. McKenzie (2010) noted that a “graffiti” paint design on the outside of a PRV-installation structure (building) in Khayelitsha had such a positive effect, reducing vandalism and contrasting “graffiti” was not added to the graffiti design provided by the City of Cape Town who owns the installation.

2.4.4 Safety

An important factor to consider when designing a sewer pump station is safety. The Occupational Health and Safety Act No 85 of 1993 stipulates that certain precautionary measures must be taken before and during entry to areas like wet well pump stations. Ventilation (discussed later in this text) is one aspect that is applicable to sewage pump stations, but not to its water supply counterpart. Wet wells must be designed to provide safe access for operational and maintenance staff. This is possible by adding grab rails at the access point and an access ladder to reach the various compartments of the pump station, including the wet well.

2.5 Emergency storage

A common perception is that pumping plant overflows are caused by power failures. This has been reported to be a major concern, but there are other instances when the pump station loses its functionality completely, e.g. simultaneous mechanical failure of duty and standby pumps, or clogging of the inlet to the sump. Emergency storage should, and – could, be provided in the pump sump and surrounds as discussed in more detail in the section on sump design. Overflow connections to adjacent sewers could be provided in cases where the system allows for such diversions upstream of the pump.

When an overflow connection into an adjacent sewer system is not available upstream of the pump station, a storage basin or retaining pond (also called buffering dams) may be provided to retain the flow for a predetermined period of time upstream of the pump sump, in order to allow the operations personnel adequate time to restore power to the pump station. Such additional emergency storage can be provided above the surface to control and monitor spills. Despite the advantages of the buffering offered by such a facility the odour and community health concerns are obviously notable. Additional emergency storage is particularly useful in all cases leading to complete failure of the pump station, but at the same time is undesirable in terms of social acceptance and public health.

Van Dijk et al. (2010) state that the minimum emergency storage capacity required at a sewage pump station is six hours of the inflow, with the storage capacity based on the future average dry weather flow (ADWF) into the pumping station, with space for the ultimate capacity as appropriate. An added criterion is that the maximum high water elevation in the storage facility should be set lower than the top of the lowest manhole in the system, basement, or other plumbing fixture upstream of the pumping station.

According to SABS (1993) the emergency storage capacity above the level at which the pump cuts in should be equivalent to the greater of at least 24h flow at the average flow rate from the building, or at least 1000 litres in cases where smaller pump stations are used; ones that for example drain a single building. This concept is also documented in the most recent local sewer design guideline provided by Van Dijk et al. (2010).

Future research into sump size could investigate whether this storage should be related to sewer size. Consider the following: for a 1500 mm diameter sewer the average daily flow rate could be 500 l/sec, so 6 hours of storage would imply a pond volume of 10 800 m^3 or four times the size of an Olympic swimming pool; for a 750 mm diameter sewer the required pond capacity would only be about a quarter of this. Suggesting 24 hr storage as a requirement would pose a space problem in some instances.

2.6 Sump design

2.6.1 Sump size

A sewage pump station is a perfect example of a control volume where the conservation of mass is to be achieved. Over a set time the inflow to the pump station must equal the outflow. Sewer spills related to overflow are the direct result of this mass balance not being achieved in that the inflow exceeds the outflow for a particular time period. The time period involved prior to a spill is of course a function of the available sump volume.

The required volume of the sump, or wet well, depends on the way the pumping station is to be operated. The determination of storage volume of the wet well should be based on the rate of inflow, size of pumps and the type of pump drive.

Pumping stations equipped with constant speed pumps will normally require larger wet wells than those with variable speed pumps. In other words, the sump size is a function of the pump operation and control, among other parameters. Some basic principles of sump design have been well documented and are reviewed here.

Each pumping station shall be provided with a sufficiently large wet well to prevent frequent pump starting and stopping. Such on-off switching of a pump is also termed cycling. The wet well shall be designed to have adequate storage capacity to sustain the pump operation without exceeding the recommended number of motor starts per hour.

The method for computing cycle time and wet well volume presented here was extracted from the Sewer Design Manual (Bureau of Engineering, 2007) and is also included in the South African Sanitation Design Guide (Van Dijk et al., 2010). The same method is also documented in some text books (e.g. Butler and Davies, 2004). The time between pump starts is a function of the pumping rate and the quantity of flow entering the pump station. For multiple-speed pumps, the pumping rate is the difference in flow between the two speed steps. The volume of the wet well between start and stop elevations for a single pump or a single-speed control step for multiple-speed operation is given by various sources and most recently reported by Van Dijk et al. (2010):

$$V = \frac{tQ_p}{4}$$

where:

V = Required wet well capacity (m^3)

t = Minimum time in minutes of one pumping cycle (time between successive starts or changes in speed of a pump operating over the control range)

Q_p = Pump capacity (m^3/min) or increment in pumping capacity where one pump is already operating and the second pump is started, or where pump speed is increased.

Van Dijk et al. (2010) note that it is good practice to also include a maximum retention time in the wet well design criteria to minimize the potential for the development of septic conditions and the resultant odours. The maximum retention time is said to be 10 minutes at average design flow rates. Brière (1999) however suggests that the maximum retention time for sewage in a pumping station wet well, or sump, is 30 minutes. Unfortunately, this requirement may conflict with the need for adequate volume to prevent short-cycling of the pumps. In these cases, multiple pumps or multiple-speed pumps should be considered to reduce the incremental change in the pumping rate and, therefore, the required volume.

It is recommended by Van Dijk et al. (2010) that the inlet sewers (pipes) are not used in the design to provide wet-well storage. This statement is supported by the project team, because if inlet pipes were used for storage, the flow velocity drops and settlement occurs, in effect converting the sewer into a long silt trap.

Wet wells must also be designed to provide safe access for operational and maintenance staff.

2.6.2 Self-cleansing

The sump should be designed to minimize solids build-up and should be self-cleansing as far as possible. The criteria documented by Van Dijk et al. (2010) state that self-cleansing could be accomplished by making the sump in the form of a trench or hopper with side slopes ≥ 45°, but steeper slopes of 60° are preferred, sloping towards the inlets of the pumps. Various publications (e.g. Czarnota, 2008; Worthington-Smith, 2011) advocate that the water level should be dropped with each pump cycle to reach the sump invert – so that floating solids could be pumped away. This concept goes hand-in-hand with optimal sump shape and pump type.

2.6.3 Air entrainment and vortex formation in the sump inlet

The wet well should be designed to provide adequate submergence to the pump suction, configured to limit vortex formation and flow rotation that could encourage cortex formation and thus cavitation. The issue of vortex formation in the sump at the pump inlet has been well documented and currently forms part of an on-going research drive at Stellenbosch University incorporating 2D and 3D finite element modelling of pump sumps as well as corresponding laboratory models (Kamish, 2010).

2.6.4 Buoyancy

High water tables are a particular concern during the design of pump sumps. When the sump is empty the effect of buoyancy would induce an upward force and cause the sump to lift. Van Dijk et al. (2010) reinforce that, in cases where there is a high ground water table and the pump sump is empty there is a risk that the structure may float and be pushed out of the ground. The necessary calculations are needed in this case to quantify the possible problem and implement anti-buoyancy measures when appropriate. This problem is not only restricted to the design and commissioning of the pump station and could not occur once the pump station is operational. When the sump is only partly full (or almost empty) the surrounding groundwater level may be significantly higher thus resulting in an upward force. This is quite possible as pump stations are usually in low lying areas.

2.6.5 Hydraulics

The layout of the wet well is determined by hydraulics, maintenance and safety considerations. This section addresses the hydraulics, with the other two discussed elsewhere in this text. Wet well hydraulics centres on a design allowing for optimal conditions at the inlet of the suction pipe. The basic criteria used in local practice (Van Dijk et al., 2010) include the following:

- The flow must be laminar
- The flow must not contain entrained air
- Vortex forming must be avoided
- With multiple suction inlets, flow must not pass by one inlet to reach the other.

2.6.6 Solids

Grit and rags are the main cause of wet well and pump maintenance. The design of the wet well should incorporate aspects to reduce the possibility of such items from entering the pump suction pipe, unless a macerator is used to shred the items.

2.7 Auxiliary equipment

Each pumping station should be designed to provide the necessary ancillary equipment to support the operation and maintenance of the pumping system. These items may, or may not include sand or rag traps, screens, macerators, and hoisting equipment to extract the pump from the station for maintenance. Johannesburg Water for example specifies that the inlet to the pump station must be equipped with macerators as well as screens to remove the solids and inorganic matter at decentralised points in the system – that is at each pump station (Johannesburg Water, 2007). Some of these matters are addressed separately in the next chapter of this report.

2.8 Sewage pumps

2.8.1 Solids handling ability

Sewage pumps should be able to pass solids that are expected in sewage. Pump designers, over the years, have taken up this challenge and have come up with a number of solutions which, to a lesser or greater extent are reasonably successful. Such items that need to be handled may include sand and sediment, grit, paper, rags and fibrous material. Differentiation is needed, because some items can float and be carried in suspension while others sink and are dragged along the sewer invert, as discussed in more detail shortly.

Despite the claims by some pump manufacturers of providing "non-clogging pumps", there is no such thing as a non-clogging pump. However, some types of pumps and impellers tend to clog less often than others. A typical local recommendation to discourage clogging of impellers in sewage pumps locally was reported by (Van Dijk et al., 2010). "Non-clog" type impeller pumps, intended for unscreened municipal applications, should have impeller clear openings capable of passing Ø 75 mm solids and should have a suction inlet of at least Ø100 mm according to the new design guideline for waterborne sanitation systems. All pump types and impellers do not necessarily meet these criteria, but it is apparent from the review presented below that many designs that are known to clog less have a capability to pass solids. The alternative, advocated by some local authorities, is to include a macerator system upstream of the pump, in which case the handling of large solids is unnecessary.

2.8.2 Pump types

Sewage pumps are normally the centrifugal type which is specifically adapted to enhance solids handling capability. These include the following basic types, each of which are subsequently discussed in this section in more detail:

- Vaned impeller
- Vortex impeller
- Impeller with shredder
- Screw centrifugal impeller

Vaned impeller

Vaned impellers are also known as radial flow solids handling impellers and are depicted in Figure 2-5. The impellers can be closed, open or semi-open. The medium passes through the eye of the impeller and is radially accelerated by the vanes, creating the centrifugal force resulting in the flow and pressure. The efficiency of typical vaned impeller pumps is reasonably high at around 70%, but the risk of clogging is also relatively high. These impellers are often used in medium to large pumping installations.

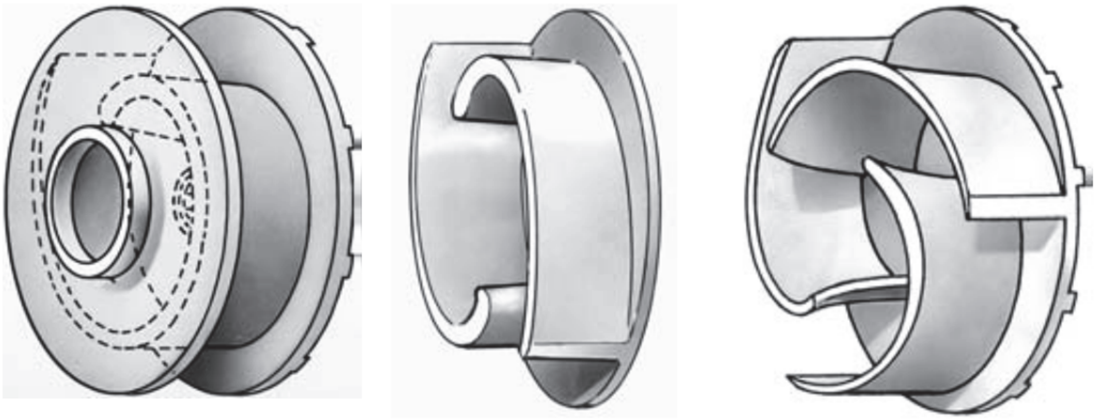


Figure 2-5. Vaned impellers (Worthington-Smith, 2011)

Vortex impeller

The principle of a vortex impeller is that centrifugal force is induced by vortex action on the face of the impeller. The sewage does not pass through the eye of the impeller. Instead it approaches the pump and exits at a 90 degree angle after being accelerated by the rotating impeller above the entry point. A typical vortex impeller is shown in Figure 2-6, with the cross section clearly showing the impeller as well as the entry and exit points. The efficiency of the vortex impeller is low (around 50%), but the risk of clogging is equally low. Vortex impellers are often used in small to medium installations where the low efficiency would not have a dramatic impact on the total energy bill.

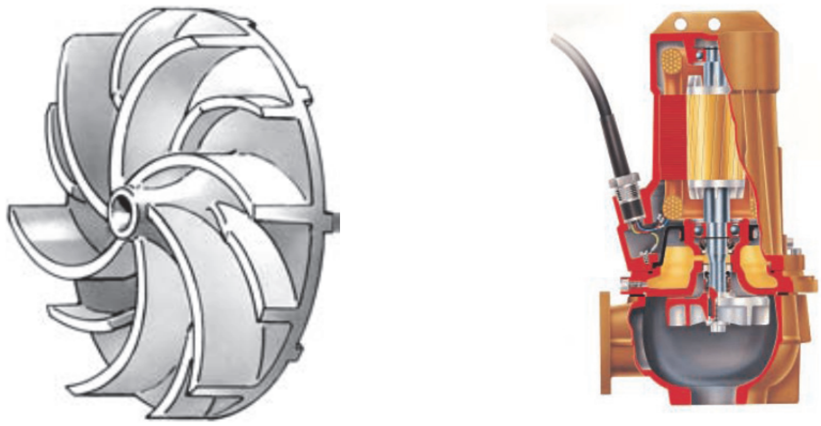


Figure 2-6. Vortex impeller (Worthington-Smith, 2011)

Impeller with shredder

Some impellers are provided with a shredder, as shown in Figure 2-7, to shred solid items in order to reduce the risk of clogging. The shredder version of the impeller macerates solids, but is not as effective in disintegrating solids as a separate macerator. The efficiency of these impellers is low (about 50%), but once again the risk of clogging is low. These impellers are often used in relatively small installations.

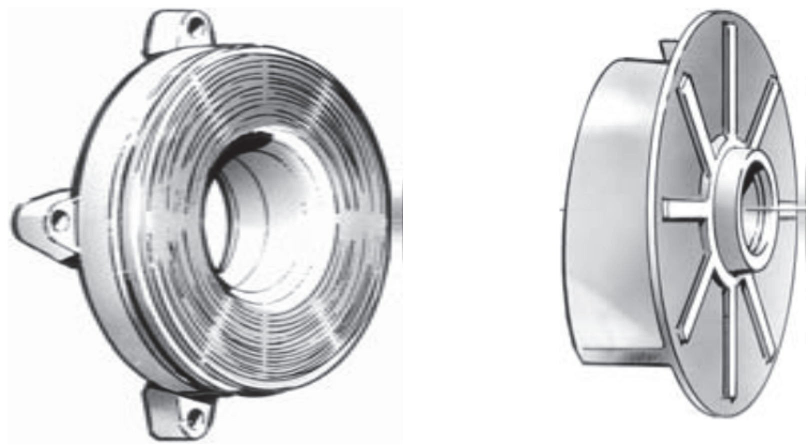


Figure 2-7. Shredder impeller (Worthington-Smith, 2011)

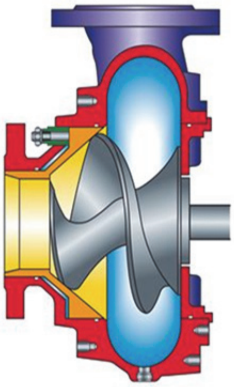


Figure 2-8. Screw centrifugal impeller (Worthington-Smith, 2011)

Screw centrifugal impeller

The screw centrifugal impeller is a hybrid, which combines the features of a positive displacement screw type pump with radial flow principles. The efficiency of these impellers is relatively high (about 70%) with a low risk of clogging. These impellers are often used in medium to large installations.

2.9 Pipework and valves

2.9.1 Pipe sizing and valves

In sewers based mainly on gravity flow the pumped sections require relatively high maintenance and induced cost in comparison to gravity pipes. It is therefore sensible to minimise the length of the rising main (Butler and Davies, 2004). The rising main is the pump discharge pipe system. The purpose of the rising main is to convey the sewage under pressure to a discharge point at an elevation that is higher than would be reached by means of gravity flow along the sewer. The exit point could be another pump wet well, a gravity sewer manhole, or the WWTW.

The design engineer should conduct a detail design of the rising main as per set criteria and design guidelines (e.g. those provided by Van Dijk et al., 2010). The most basic of these is that the minimum design velocity should be 0,7 m/s to maintain solids in suspension. The recommended velocity would normally be between 0,9 to 1,2 m/s, with the maximum velocity not exceeding 2,5 m/s for short periods at peak flow conditions. The authors cited above also provide a detailed guide pertaining to design of pipe work inside the pump station. According to Maxwell (1993) the diameter of the rising main can be provisionally established by applying a pumping velocity of between 0.8 and 1.2 m/s to maintain self-cleaning abilities, and to minimise friction losses from excessive velocities.

A local engineering firm specialising in hydraulic modelling and planning of water and sewer systems apply the principle that the minimum design velocity, as stipulated in the appropriate design criteria, should be exceeded at least once a day (GLS, 2010) for scour purposes. Thus for variable speed pumps the maximum flow should ensure that the minimum velocity is exceeded and continuous pumps should pump at a flow where the minimum velocity is exceeded. For variable speed pumps it is thus assumed in planning models that the minimum velocity is exceeded once a day. Rising mains leading from variable speed pumps should therefore be designed using the maximum flow rate feeding into the pumps.

2.9.2 Pipe material

The most common material for small diameter gravity sewer pipes such as those used for urban services, is uPVC. Other materials such as concrete and GRP are generally used for sewers of 300 mm in diameter and larger. The material cost is a significant factor when selecting the rising main pipe material, where the pressures are higher. (Van Dijk et al.,2010) note that the environs of a sewage pump station can be mild to very corrosive and state that pipework must be suitably protected, by using linings, or coatings.. The most common materials used locally for rising mains are epoxy coated mild steel, lined mild steel, stainless steel, reinforced concrete and ductile iron. In some high pressure and/or relatively large rising mains, cement mortar lined and coated steel are used. In smaller applications uPVC may be used, but this is often subject to approval by the local authority (Van Dijk et al., 2010).

The Bureau of Engineering (2007) provides a comprehensive list of factors to be considered when selecting a pipe material in addition to cost. The key issues in the list are corrosion (internal and external), erosion, ground conditions, external loading, operating and surge pressures and construction methods. A detailed report on designing for corrosion in sewers (Goyns, 2009a) and for evaluating external loads (Goyns, 2009b) is available for further reading.

(Van Dijk et al.,2010) report that the most common problems with rising mains are related to corrosion, both internal and external. Internal corrosion is normally caused by hydrogen sulphide accumulation inside the pipeline, mainly at high points in the piping system. External corrosion is normally found where the pipe is in contact with aggressive water, corrosive liquid or corrosive soils. All pipe materials bar plastics are susceptible to corrosion by acids.

Ductile iron or mild steel pipe work and fittings are recommended by (Van Dijk et al.,2010) for use in the pump well, valve pit and between the last manhole and the pump sump. However, all non-plastic pipes conveying sewage are to be epoxy lined.

2.9.3 Thrust blocks

Pipes subjected to internal pressure are subject to unbalanced forces at bends and transitions due momentum. To ensure that they stay in place such pipelines should be designed with the support to prevent undue deflection, vibration, and stresses on the pipe elements as well as the appurtenant equipment and structures. This is provided by thrust blocks and mounting brackets that produce the reactions to resist the unbalanced hydraulic forces.

2.9.4 Valves

The most common types of valves encountered in sewage pump stations are:

- Isolating valves
- Non-return valves
- Air valves.

Each of these types of valves is discussed briefly below by considering the key aspects in each case by means of bullet lists. Van Dijk et al. (2010) provide more information as well as a figure showing the typical application of valves and pipework in and around a typical sewer pump station.

Isolating valves

- Isolating valves are required on both the suction and delivery sides of the pump mainly to facilitate the removal of pumps for maintenance purposes

- Gate valves only are suitable because full bore opening is attained

- Valves shall as far as possible be located in horizontal pipework to prevent the build-up of grit on the downstream side of the valve

- Valves shall as far as possible be installed in the vertical position

- Large valves shall be fitted with actuated gearboxes to facilitate the opening and closing

- According to Van Dijk et al. (2010) isolation valves of same diameter as sewer main should be used. The valve should be placed on the sewer main either in the manhole immediately prior to the pump station or in the pump station. The type of valve is to be a sluice valve, or where space is insufficient to accommodate a sluice valve, a knife gate valve should be used. Sluice valves used as rising main isolation valves should have a cast iron casing and bronze wedge.

Non-Return Valves

- Non-return valves are required on the delivery side of the pump to prevent the emptying of the rising main when the pump stops; to prevent the flow from short-circuiting in a multiple parallel pump installation and as a dampening device for pressure surges when the pump starts-up and stops

- Non-return valves should be located in horizontal pipework to prevent the build-up of grit on the downstream side of the valve

- Van Dijk et al. (2010) also note that non-return valves of swing check type with cast iron casing and bronze disc are the preferred type to be used for sewage applications.

Air valves and blow-offs

- Air valves will be needed at the pump station to reduce the effect of pressure surges

- Van Dijk et al. (2010) and Van Vuuren et al. (2004) suggest a procedure to size air valves and to aid with their positioning

- The type of air valve to be used could for instance be a Vent-O-Mat RGX or equivalent suitable for sewerage application

- Blow-off valves are also required at all low points along a rising main pipe system.

2.10 Standby capacity

2.10.1 Standby pumps

All sewage pump stations must have standby pumping capacity. The degree of standby will vary between 100%, in a single pump installation and a lesser percentage in a multiple pump installation. The typical design capacity of a sewage pump station is to accommodate the peak wet weather flow. It is good practice to design the pump station so that there is always at least one standby pump and also to ensure that, as far as practically possible, that a minimum of two pumps should be permanently installed at each pump station, as one may be doing maintenance work elsewhere.

2.10.2 Electric power supply

Van Dijk et al. (2010) comment on the need for backup power in the recently compiled sewer design guide. Following recent localized power supply problems, the reliability of energy supply is a concern. It is recommended in the design guide that all pump stations be designed with the facility for emergency power. Larger pump stations should have permanent diesel driven generator units with an automatic transfer switch to ensure automatic transition from ESKOM's electric supply to a diesel generated electric supply. Smaller pump stations should be supplied with portable generators, or at least provision should be made for portable generators.

2.10.3 Portable emergency equipment

As stated above, portable generators could be used to drive smaller pumps in times of emergency. In addition it may be useful to design pump stations with an easy access in cases where suction tankers or portable pumping equipment is needed to alleviate a more significant problem (e.g. mechanical failure of all pumps).

2.11 Pump control

2.11.1 Overview

Butler and Davies (2004) provide a sensible starting point for understanding pump control in explaining that, while the pumps are running, the level in the sump is falling (or at least is supposed to fall). At some reduced fixed level in the sump the pumps are automatically turned off so that the level starts to rise again due to the steady inflow of sewage. Then when an upper set level is reached that the pumps are turned on. This cycle is repeated indefinitely. All pumps thus require some type of control.

Sewage pump stations invariably have automatic pump control with start/stop commands to the pump provided by level controls in the wet well as described above. Recent work by Van Dijk et al. (2010) makes for good reading on the matter. The text in this section was mainly adopted from the design guide cited above. The aspects that are relevant here include notes on wet well design, level controls and methods for controlling the pump delivery rate.

2.11.2 Wet well design in terms of pump control

Pump control is integral to the wet well design, since the levels and thus pump switching is a function of the storage volume in the wet well. The wet well should be designed with adequate storage capacity to sustain the pump operation within these limits. In other words, the pumps should operate without exceeding the recommended number of motor starts per hour as presented in Table 2-1 (adopted from Van Dijk et al., 2010). The same authors also state that it is good design practice to allow for the maximum retention time in the wet well design as is practically possible instead of only allowing for a well size that would result in the minimum cycle time of the pump.

Table 2-1. Pump control criteria (Bureau of Engineering, 2007)

Motor (kW)	Maximum starts per hour	Minimum cycle time (minutes)
Up to 35	6	10
45 to 55	4	15
70 and larger	2	30

The primary level control is typically some type of ultra-sonic level sensing device. Van Dijk et al. (2010) suggest that the level sensor should be mounted inside the wet well as recommended by the manufacturer, but above the high water level. The level switch should be positioned in line with the suction pipe and away from any possible turbulence. The mounting design should allow for easy cleaning of the sensor. Float type level switches should be included as back-ups in case of failure to activate the low level cut-off for the pump and the high level emergency alarm.

2.11.3 Methods for pump control

Van Dijk et al. (2010) provide a description of pump control methods and list two common methods of pump control, with a third as the two methods combined. The two methods are the use of constant speed pumps with level control in a well-designed wet well, and variable speed pumps or variable speed drive (VSD) pumps, with matched flow control. Van Dijk et al. (2010) also identify multiple pumps, combinations of small and large pump units, all VSD pumps, and a combination of constant and VSD pumps as additional methods for pump control.

Constant speed pumps with so-called “fill-and-draw” control usually require a larger wet well storage volume in order to provide enough capacity to limit pump cycling. This method is commonly used for pump stations with relatively smaller capacity with adequate space for large wet well construction. VSD pumps in turn are used with "matched flow” control and require smaller wet wells to achieve the same cycling frequency as constant speed pumps would for a given wet well size. In addition, VSD pumps produce less hydraulic surges and smoother flow variation than constant speed pumps.

The two types could effectively be used in combination, where the VSD pump would trim flows in excess of what the constant flow pumps could handle. The best choice is considered by Van Dijk et al. (ibid.) to be the one which provides the best overall pump station efficiency, range of operation, and reliability.

2.11.4 Multiple pumps

Large pump stations normally have multiple pumps to deal with the diurnal and seasonal variations of the incoming flow. Specific design features of a multiple pumping installation may include identical pumps connected in parallel or series, and planned rotation of pumps used for duty and standby purposes.

2.11.5 Electrical systems and electronics

Van Dijk et al (2010) provide significant detail regarding electrical and control equipment, including the power supply, transformers, motor control centres, switchgear, electric motors, electric variable speed drives, electrical wires and conduits, lighting fixtures, and other associated interface with the instrumentation, control systems and telemetry.

2.12 Pump efficiency and optimal pump selection

2.12.1 Pump sizing

A pump station should be capable of delivering the required flow rate at the required head. From experience of municipalities, pump sizing can be based on PDWF of 3 times the ADWF. The PWWF is estimated as 1.5 times the PDWF (Shand, 1993). The typical design capacity of pump station is to accommodate PWWF with at least one standby pump.

Sewage inflow rate may vary significantly and makes the pumping task challenging. There are generally three sewer pumping methods used. The combination of constant speed pumps, VSD pumps and sump size has been discussed before. A combination of the two drive types is useful where the VSD pump is used to control the excess flow over and above the constant flow handled by the constant speed pump. When the flow demand is expected to increase, the design of a pump station should be of such a nature to accommodate extra pumps for future flow capacities (GLS, 2010).

Various pump configurations are available and it would thus be necessary to optimise the layout in terms of the best economical solution. This could be done through a cost analysis enabling the designer to compare the different solutions, but attention to potential future problems are often neglected in that the cheapest (most economical) selection is made based simply on financial criteria such as capital cost and operations and maintenance cost.

When comparing the existing capacity of a sewer pump station with the estimated future flow to be delivered, software packages are often used to “resize” the pumps in order to gain a first order estimate of the required capacity. Pump structures in hydraulic models that have insufficient capacity, as well as continuous flow pumps, are resized during typical master planning analysis of sewer systems (GLS, 2010). The new capacity of the pump station is then set equal to the total expected future flow rate at some point in time arriving at the pump station plus the required user defined relative spare capacity. The latter spare capacity allows for storm water ingress. In cases where more than one pump is connected to a pump structure the new capacity is allotted to the first pump and all subsequent pumps are given zero capacity. This implies that the software used in typical planning models locally provides the user with the total required duty capacity of the entire pump station (as if it were a single pump), thus allowing the designer to select individual pumps, assess the layout and connectivity of the pump/s and then to add standby pump/s as needed prior to moving on to the design of the pump station.

2.12.2 Pump selection based on duty point and efficiency

Van Dijk et al. (2010) present a basic 5-step process for selecting the most suitable pump based on pump theory, thus disregarding non-hydraulic aspects such as risk and expected future problems. The steps presented below are adopted from Van Dijk et al. (2010) without extension and could form the basis of an output from this project, where presentation of a stepwise procedure could aid planners and engineers by also incorporating aspects pertaining to risk and expected future problems. The 5-step pump selection process involves:

- Step 1: Determine the range of flows for which the pumping station should cater. Sewer pump station design capacity must include an allowance for extraneous flow. Proper design and construction will reduce the amount of water entering the sewers, but this should not nullify the contribution of possible unwanted flows.

- Step 2: Determine the diameter of the rising main based on velocities and operational criteria; Van Dijk et al. (2010) suggest that the minimum diameter for the rising main should be 100 mm, although some local authorities allow 75 mm if a macerator system is installed.

- Step 3: Calculate the suction head loss, discharge head loss, friction head losses and static height difference for system, taking into account the variations in parameter values over the expected design life

- Step 4: Compile the system curve, superimpose the pump characteristic curve/s and identify the possible design point (duty point). At this stage economic evaluation can be performed by comparing various rising main diameters and costs with pump station sizes and costs

- Step 5: Pump selection. Plot the design point on the pump curve which is the intersection of the flow and head. The design point should be at or near the best efficiency point. This step would also involve a determination of the type of pump suitable for the application, the type of impeller and verification that all criteria are met (e.g. lowest efficiency and NPSH requirement). The designer would determine the number of pumps and configuration needed to meet the estimated flow range.

3. SEWAGE AND SOLIDS

3.1 Basic considerations

Van Dijk et al. (2010) provide a recent summary of the basic flow capacity, hydraulic design, and equipment/material requirements for sewer pump station facilities. The purpose of the work cited above was to report on design guidelines and to establish standard design criteria for sewage pumping station design in South Africa. A review of the basic hydraulics and design criteria is essential in moving towards the ultimate goals of this project. For the purpose of this text the work by Van Dijk et al. (2010) was used as main reference and much of the flow and text in this chapter was adopted from it.

3.2 Sewage flow rate and solid load

3.2.1 Flow rate

The capacity of a wastewater system is based on assessing essential parameters, of which flow rate is one of the most notable. Flow rate is expressed in different ways. The most frequently used are the dry weather flow (DWF), average dry weather flow (ADWF), peak dry weather flow (PDWF) and peak wet weather flow (PWWF). Estimates of extraneous flows are often added. The hydraulic capacity of gravity sewers is usually designed to accommodate the PDWF whilst flowing partially full (typically at 50% to 70% of full flow capacity). Butler and Graham (1995) provided a comprehensive assessment of modelling DWF in sewer networks based on inflow from individual household appliances, taking into account the spatial distribution of the inflows. They showed that it is possible to accurately model the sewer flow pattern by means of such detailed models. The advantage of this concept is that the peak flow is directly available from the model as the maximum value on the flow rate axis when plotted against time. However, the practical application of such detailed models in South Africa is limited and is unlikely to become popular due to the high input data requirements.

The flow rate in sewers could be influenced by various factors such as the time of day, time of year, weather, deposition of sediment, slime, pipe size and pipe slope. According to Ashley et al. (2004) the most significant parameters that impact sewer flow rate:

- Dry weather flow rate and concentrations
- Period of the day
- Rainfall intensity and duration (infiltration)
- Antecedent dry weather period
- Amount and type of deposits in system
- Amount and growth rate of slime (slime growing inside pipes)
- Age and condition of sewer fabric (pipe corrosion)
- Sewer maintenance and cleaning practices
- Sewer geometry, size and slope.

3.2.2 Peak flow rate and peak factors

The flow conditions in sewers vary by time of day. Peak flows normally occur during the mornings and evenings, although diurnal patterns have been noted to be site specific. Pump stations serving areas with schools, collect their peak flows during the break periods at school. Industrial facilities sometimes release their effluents during the night to avoid the daily peak flows.

The pump flow rate must equal the maximum inflow rate. This peak flow is typically determined by estimating the average flow, then multiplying it by a peak factor. A peak factor of 3 is typically used for estimating peak flows in relation to average daily flow rate. Van Dijk et al. (2010) note that peaks vary from one region to the next and that a site-specific analysis is preferred.

To take advantage of the attenuation of peak flows in gravity sewer systems as the contributor area and population increases, design peak factors may be reduced according to the CSIR (2003) graph showing the relationship between the peak factor and population served, as reproduced in Figure 3-1. If actual attenuation factors are available for the area under study, however, these should be used instead of those presented by the CSIR (2003). Actual maximum peak flow could be recorded from logged records of sewage flows at strategic points on the sewers (say at the last manhole upstream of the pump inlet) for the area under investigation. The peak flow would be site-specific and representative for the record period only.

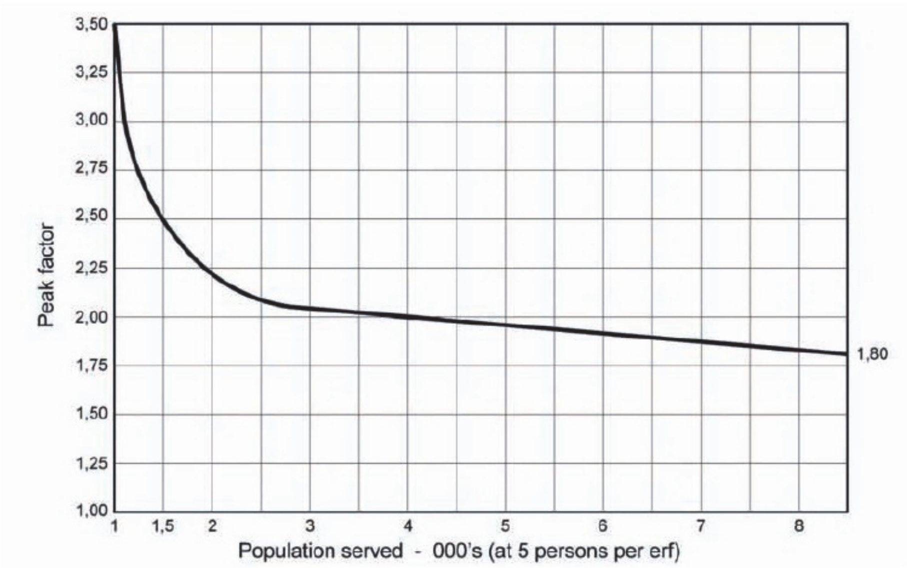


Figure 3-1. Attenuation of sewage flow and peak factors (CSIR, 2003)

3.2.3 Minimum flow velocity criteria

The minimum flow velocity is often used as design criteria for sewers in order to prevent unwanted settlement of solids and grit. Table 3-1 illustrates a few minimum flow velocities used as design criteria for different countries. This is in fact not the minimum flow velocity in the system (which could of course be zero for some periods of time); it is the lowest velocity that the maximum daily peak value should provide in order to flush the system clean at least once a day.

3.2.4 Flow rate estimation

The CSIR (2003) provide a detail example of calculating sewage flow rates. The average daily dry weather flow (ADWF) is used with options for selecting a single dwelling unit (du) on the basis of different income groups. With a peak factor, which is a function of the population served (as discussed elsewhere in this document) and an infiltration rate of 15% the design flow is determined for each of the income groups. The reported unit flows vary from low income (0.0167 l/s per du), middle income (0.0250 l/s per du) to high income (0.0333 l/s per du).

Table 3-1. Minimum flow velocity criteria (Ashley et al., 2004: 253)

Source	Country	Sewer Type	Minimum velocity (m/s)	Pipe Conditions
American Society of Civil Engineers (1970)	USA	Foul	0.6	Full/half full
British Standard BS 8001 (1987)	UK	Storm	0.9	Full/half full
		Storm	0.75	Full
		Combined	1.0	Full
Minister of Interior (1977)	France	Foul	0.3	Mean daily flow
		Combined	0.6	For a flow equal to 1/10 of the full section flow
		Separate storm sewer	0.3	For a flow equal to 1/100 of the full section flow
European Standard EN 752-4 (1997)	Europe	All Sewers	0.7 once per day for pipes with D<300 mm, 0.7 or more if necessary in sewers larger than D = 300 mm	N/A
Abwassertechnishe Vereinigung ATV Standard A 110 (1998) (replaced by ATV 110 (2001))	Germany	Foul Storm Combined	Depends on diameter of pipe ranging from 0.48 (D=150 mm) to 2.03 (D=3000 mm)	0.3 to full for 0.1 to 0.3, velocity plus 10%
CSIR, 2003	South Africa	Foul sewers	Minimum velocity is 0.7 m/s for all diameter pipes	

A more detailed description is provided by Van Dijk et al. (2010) in the recent waterborne sanitation design guide. The document states that the design flow is usually based on the type of residential unit drained, potential infiltration, peak factors and attenuation in the network. It is also noted that many Municipalities have developed their own design standards and it may be required from the designer to use these values. This is particularly applicable in the large metropolitan areas of Tshwane, Johannesburg, Ekurhuleni and Cape Town. The SABS (1993) provide anticipated sewage flow rates for different types of water users, as shown in Table 3-2.

Table 3-2. SABS (1993) design flows as reported by Van Dijk et al. (2010)

Flow from dwelling houses or dwelling units with full in-house water reticulation	
Description	**Sewage flow (l/day)***
Low-income group:	
Per dwelling unit, or	500
Per person per dwelling unit	70
Middle to upper-income groups:	
Per person per dwelling unit, or	160
Dwellings with 2 bedrooms	750
Dwellings with 3 bedrooms	900
Dwellings with 4 bedrooms	1100
Dwellings with 5 bedrooms	1400
Dwellings with 6 bedrooms	1600

Note: * An allowance of 15% for storm water infiltration and other contingencies should be incorporated in the design figures to be used for dwelling houses.

Sewage flow from dwelling units that do not have a full in-house water reticulation	
Level of water supply	**Sewage flow (l/person/day)**
Public street standpipes	12 to 15
Single on-site standpipe with dry sanitation system	20 to 25
Single on-site standpipe with a WC pan connected to water supply	45 to 55
Single in-house tap with a WC pan connected to water supply	50 to 70

Sewage flow from non-residential buildings		
Type of establishment	**Unit**	**Daily sewage flow (l/unit)**
Airports	Passenger	10
Bars	Customer	8
Boarding houses	Person	110
(Additional kitchen wastes for non-residential boarders)	Person	23
Cocktail lounges	Seat	70
Country clubs	Visitor	30
	Employee	50
Day schools	Student	37
Department stores	Toilet	1850
	Employee	40
Dining halls	Meal served	30
Drive-in theatres	Car space	9
Factories (exclusive of industrial waste)	Worker/shift	140
Hospitals, medical	Bed	500
	Employee	40
Hospitals, mental	Bed	400
	Employee	40
Hotels without private bathrooms	Person	110
Hotels with private bathrooms	Person	140
Motels	Bed	90
Offices	Worker/shift	70
Restaurants (toilet and kitchen wastes)	Patron	20
Service stations	Vehicle bay	10
Shopping centres	Parking space	5
	Employee	40

Swimming baths	Person	9
Theatres	Seat	10
Tourist camps or caravan parks with central bathhouse	Person	90

3.2.5 Pumping requirement for extraneous flow

Sewer design capacity must include an allowance for extraneous water components which inevitably become a part of the total flow. Extraneous flows are discussed in detail by Stephenson and Barta (2005a and 2005b). These flows may comprise uncontrolled surface inflow, groundwater infiltration, and stormwater ingress. The inflow of stormwater and infiltration of groundwater into sewers are considered common phenomenon both internationally and locally. In South Africa extraneous flows are found to be seasonal, are a function of rainfall intensity, land use and some other parameters describing the drainage basin. Unnecessary pumping is of course required to convey the extraneous flow with the arriving sewage, as it is obviously mixed. Wet weather periods may require overflow bypassing or additional storage capacity to compensate for serious storm ingress.

3.2.6 Stormwater ingress

In South Africa, the design criteria reported by Van Dijk et al. (2010) state that, for large diameter sewers the pipe size in gravity main allows for the peak dry weather flow to occupy 50% to 70% of the pipe's capacity. The remaining 30% to 50% of the pipe flow is reserved for conveying stormwater ingress in times of high rainfall. The inflow of stormwater during a storm can cause a sharp and sudden increase in flow rates in sewers, as observed during various sewage flow logging events over the years (Van Dijk et al., 2010 and Still et al., 2011). According to Stephenson and Barta (2005a) a 100 m^2 paved area located around a broken manhole cover could result in 5 m^3 of stormwater ingress from rainfall of 50 mm per day. The effects of stormwater ingress on peak flow rates to be handled by the system could be up to 5 times as high as the ADWF. These values were also cited by Van Dijk et al. (2010) in the sanitation design guide.

3.2.7 Groundwater infiltration

Stephenson and Barta (2005a) underscore the fact that gravity sewers in urban areas usually follow the watercourses along the valley floors and may even be situated below the bed of the adjacent stream. This suggests that these sewers could receive relatively large quantities of groundwater through cracks and pipe joints, whereas sewers built at higher elevations will receive relatively small quantities of groundwater.

Infiltration is given as a flow rate (l/s) per unit pipe diameter, unit of pipe length and unit of time. The pipe material and its condition may also have to be considered in determining infiltration (for example old clay pipes that have cracked or concrete pipes that have corroded). The infiltration rate and quantity has been reported by Stephenson and Barta (2005a) to depend on the length and diameter of the sewers, the total surface area of the drainage basin, the soil and topographic conditions, and the density of house connections. The amount of groundwater flowing from a given area may vary from a negligible amount for a highly impervious area or one with dense subsoil to 30% of the rainfall for a semi-pervious area with sandy subsoil. A high groundwater table would result in more leakage into the sewers and a larger increase in the quantity of wastewater than would occur with a lower water table. In all cases the infiltration would have to be allowed for when designing a sewage pump station.

3.2.8 Plumbing leaks to the sewer system

A proportion of unwanted inflow to sewers is generated from plumbing leaks where potable water enters the sewer system. The main causes are leaking toilets and bathroom appliances, but building foundation drains and swimming pool filter backwash waster could also be classified as leaks in this regard. This inflow component is difficult to identify and it is commonly measured with infiltration and is not addressed separately in this study.

3.2.9 Exfiltration and possible reduction in future flow rate

Ellis et al. (2004) investigated the impact of exfiltration from urban sewers. In addition to exfiltration resulting in reduced flow rates, Van Dijk et al. (2010) remind that there could even be a reduction in the sewage flow rate over time due to interventions such as water conservation and demand management, increased on-site reuse of grey water, reduction in infiltration and stormwater ingress. It makes little sense however to incorporate such potential reductions in flows during the design of sewage pump stations due to the uncertainties involved in predicting the impacts thereof and ensuring that these interventions are implemented as expected.

Aged sewers are reported to be the most significant characteristic governing exfiltration from sewers (Van Dijk et al., 2010). Leaking sewers are an environmental concern. However, it does not make sense to incorporate exfiltration in pump design to reduce the pump design flow rate. For this reason exfiltration along the gravity pipe system is neglected when it comes to the hydraulics of sewage pump station design. Exfiltration per se (thus not referring to surcharging sewers and sewage spillages) is also not considered to contribute to problems at pump stations.

Another reason for not reducing flow due to exfiltration is that infiltration and exfiltration are linked. When pipelines have deteriorated there can be exfiltration during the dry season and infiltration during the wet season.

3.2.10 Solid load

Pump size is dictated by the flow rate and required head, but the solid load complicates the pump selection (when compared to pumping clean water). During wet weather flow rain and storm water infiltrates the sewers. The total mass of solids in combined sewers can be 5 to 10 times more in wet weather than in dry weather periods (Ashley et al., 2004). There are no reasons why the same would not hold true for separate sewers, but this finding was not noted in the literature during the extensive knowledge review.

The content and relative contribution of solids type to the total solids varies from one catchment to another and is influenced by the flow rate in various ways. The solid load by mass for industrialised countries has been reported to vary between 100 mg/l and 500 mg/l for sanitary solids and between 50 mg/l and 1000 mg/l for storm water solids (Ackers et al., 1996). Czarnota (2008) reminds that, although the concentration of solids mass per volume of water may appear to be low, the gross quantity of solids passing through the system may be significant. The total solids mass is proportional to the sewage flow rate. When a disturbance in the flow of solids occurs, the solids concentration tends to increase rapidly and could result in clogging. The range of flow rates in sewers results in a variation of the solids and sediment transport rates. In small sewers, such as those in reticulation systems with intermittent flows, most solids settle out in between flush waves and peak flow periods.

3.3 Problems associated with solids in sewers

The presence of unwanted solids in sewers causes problems. Ashley et al. (2004) listed some effects of solids on sewers, presented in Table 3-3. These problems are all associated with solids in combined sewers, but most are considered directly applicable to separate sewers as well.

Table 3-3. Effects of solids in sewers (Ashley et al., 2004: 165)

Effect caused by Solids	Description of solids cause
Reduction in hydraulic capacity, increase in surcharging, flooding	Deposition of solids in inverts, permanent or semi-permanent
Blockage	Deposition in inverts, build-up on walls (progressive or sudden)
Gases, odours, explosions	Generated from biological degradation in bed deposits (hydrogen sulphide, methane and other odorous substances)
Sewer corrosion	Generated from biological degradation in bed deposits in moist atmosphere
Pump impeller abrasion	Inorganic solids in flow (typically washed through system in wet weather)
Screen blockages and damage	Large solids (organic and inorganic)
Shock loads to treatment plants	Foul flushes and bed erosion, releasing both solids and associated pollutants
Rodents (Rats)	Source of food (organic solids)
Health risk to sewer workers	Increased hazards, infections: gases (asphyxiation, toxicity), rodents (disease transmission) Access and maintenance problems increased by solids' presence
Fat and grease deposits – can reduce capacity or get washed out in lumps	Build up in sewer walls, particularly around ambient surface levels; can also develop into balls.

3.4 Composition of solids in sewers

3.4.1 Classifying sanitary waste items

Due to the variety of flow regimes and operational characteristics, the behaviour of solids in sewers cannot be generalised. It is better to predict the nature of solids by local observations or measurements than to compare it with published averages (Ashley et al., 2005). However, some useful work has been presented on the nature of solids in sewers. The specific gravity (SG) of solids has been noted to describe behaviour to some extent and defines where the solids will accumulate, say in a pump sump. It is obvious that some objects would generally float along the system at the water-air interface and may get stuck on the sewer walls, while others would sink to the pipe invert and tend to settle, dependant on SG value of the solid material. Table 3-4 presents three classes of solids based on their SG values as adapted from Czarnota (2008).

Table 3-4. Specific gravity of solids (Czarnota, 2008).

Buoyancy	SG	Type of solids
Settling solids	SG > 1	Inorganic such as grit, sand, silt and also rags, clothing and some heavy organic matter
Neutral-buoyancy Solids	SG = 1	Most organic matter and sanitary items such as paper, plastics, string and cotton buds
Floating solids	SG < 1	Fats, oils, plastics, hollow objects and light organic matter

In a period from 2007 to 2008 a total of 30 screenings samples were collected at three WWTPs in Rhône-Alpes, France (Le Hyaric et al., 2009). The samples were taken from combined and partially separate sewers at screens with bar openings ranging from 3 mm to 60 mm in size. All the samples were dried at 80°C for a period of one week to determine their dry mass. A total of 3.6 tons of wet solids mass was collected during the exercise. Le Hyaric et al. (2009) divided the findings into the categories presented in Table 3-5.

The predominant fraction was sanitary textiles with 67.7% to 76.1% of the total dry mass recorded for this type of solid. Sanitary textiles were followed by so-called fines (size <20 mm), representing 13% to 19% of the total dry mass. These values are site specific and only applicable to this region in France, but are indicative of what could be expected. The categories identified in this case study helped with the categorisation of the solids in this paper.

Table 3-5. Characterization of screenings (Le Hyaric et al., 2009)

Screenings Fractions	Fraction components
Sanitary textiles	Tampons, sanitary towels, wipes
Fine fraction (<20 mm)	Ash, sand, broken glass, vegetal waste and fine residues that pass the sieve
Vegetal	Cut Grass, herbs, flowers, twigs, branches, leaves
Paper, cardboard	Newspapers, packages, brown corrugated cardboard, paper rolls, office paper
Plastics	Plastic bags, plastic films, plastic containers, pipes, pens, toothbrushes, tubes of toothpaste, condoms
Textiles	Natural fibre textiles (cotton, wool, linen) and synthetic fibre textiles (tights, sport bags)
Metal, Aluminium	Cans, keys, tools and all ferrous and nonferrous materials
Composites	Packaging made of several materials (paper, plastic, aluminium) not separable (packaging coffee, milk box and juice box)
Combustible	Crates, boxes, wood (planks), leather (shoes, bags) and rubber
Incombustible	Glass, minerals and other inert materials not classified in other categories such as ceramics, pottery, porcelain, brick, plaster

3.4.2 Categories of solids

The lack of data about solids in foul (separate) sewers makes it a difficult task to label and categorise these solids. Characteristics of screenings differ between areas and systems. Solids in sewers cannot be generalised due to the variety of contributing factors such as flow regimes and operational characteristics (Ashley et al., 2005). It was considered appropriate as part of this study to identify three main types of unwanted matter in sewers:

- Relatively large solid objects (solids);
- Sand and grit; and
- Fats, oils and grease (FOG).

Many solids found in sewage originate from bathrooms. These solids include female sanitary items including sanitary towels, panty liners, stocking, condoms, tampons and general bathroom refuse such as cotton buds and dental floss (Gouda et al., 2003). Polypropylene-based cotton buds are known for orientating themselves in such a way as to escape through even the very finest of screens as depicted in Figure 4-1 (Ashley et al., 2005). Low income areas are expected and reported to have more inorganic suspended solids than high income areas. The system layout, the number of pumps, bends and turbulence can change the composition of screenings along the flow path. Table 3-6 presents a good example of the composition of screening at three different WWTPs.

Table 3-6. Constituents of screenings (Sidwick, 1984: 29)

	Wastewater Treatment Plants		
	A	B	C
Catchment Area	Compact city with peripheral settlements	Compact town with peripheral settlements	Compact holiday resort with camps and caravan sites
Type of Flow	Gravity but 22 pumping stations in catchment area	Mainly gravity but 13 pumping stations in catchment area	Gravity and pumped with some pumping stations in catchment area
Screenings removal	100 m manually raked bar screen	25 mm mechanically-raked bar screen	Mechanically-raked bar screen with disintegration of screenings and return to flow downstream
Visual analysis of screenings from screens (by volume, %)			
Rags	70	64	15
Paper	25	25	50
Rubber	-	-	5
Plastic	5	5	20
Vegetable matter	-	1	5
Faecal matter	-	5	5

In South Africa alternative materials are often used for sanitary purposes. These items include newspapers, magazine papers, plastic bags and sand (Steyn, 2010). It has been reported that low income groups (and/or those poorly educated) make use of newspaper and stones for anal cleansing instead of toilet paper with blockages downstream as a result (Little, 2004). There are reports of motor vehicle tyres and even an old engine block that have been found clogging sewers (WRC, 2010). With the help of literature, site visits and interviews a list of solids reportedly found in Western Cape sewers was compiled, as shown in Table 3-7.

Table 3-7. Index of solids in sewers

Category	Object	Entry point
Cotton and wool products	Bandages	Toilet
	Clothing	Toilet/Manhole
	Cloths	Toilet/Manhole
	Rags	Toilet/Manhole
	Stockings	Toilet
	Under pants	Toilet
FOG products	Carbon black	Kitchen Sink/Restaurants/Manhole
	Fats	Kitchen Sink/Restaurants
	Food/Fruits/meat	Kitchen Sink
	Grease	Kitchen Sink/Restaurants
	Oils	Kitchen Sink/Restaurants
	Paint	Gutter/Gulley/Sink
Solids from the human body	Faeces	Toilet
	Foetus (human body)	Toilet/Manhole
	Hair	Shower/Bathroom Basin
	Nails	Toilet
Indestructible solids	Bricks	Manhole
	Cement	Manhole
	Glass	Toilet/Kitchen Sink/Manholes
	Rocks	Toilet/Manhole
	Sand	Toilet/Manhole
	Motor vehicle tyre	Manhole
Leather products	Hand bags	Toilet
	Shoes	Toilet/Manhole
	Wallets	Toilet
Metal products	Cans	Toilet/Manhole
	Cell phones	Toilet
	Electrical appliances	Toilet/Manhole
	Hair braids	Toilet/Bathroom
	Jewellery	Toilet
	Keys	Toilet
	Tools	Toilet
Other solids	Cigarettes	Toilet
	Feathers	Manhole
	Goldfish	Toilet
	Leaves	Toilet/Manhole
Paper and wrapping products	Magazine Paper	Toilet
	Milk boxes	Toilet/Manhole
	Money	Toilet
	Newspapers	Toilet
	paper wrapping (chips)	Toilet/Manhole
Plastic	Condoms	Toilet
	Plastic bags	Toilet/Manhole

Category	Object	Entry point
	Plastic bottles, bottle caps	Toilet/Manhole
	Plastic toys	Toilet
	Toothpaste caps	Toilet
Sanitary Textiles	Baby nappies (diapers)	Toilet
	Cotton buds	Toilet
	Cotton wools	Toilet
	Dental floss	Toilet
	Tampons and sanitary pads	Toilet
	Toilet paper	Toilet
Wood products	Matches	Toilet
	Twigs	Toilet/Manhole

FOGs are insoluble and deposit along the sewer system and frequently cause blockages (FOG) (He et al., 2011). Of all the storm sewer overflows that occur in the United States about 48% are due to sewer line blockages, of which 47% are related to FOG deposits that constrict flow in pipes (He et al., 2011). FOG deposits also build up around level probes which then get stuck or malfunction, resulting in the pump burning out or overflowing of the sump. Devices are available to remove FOGs, but were not investigated at this phase of the project.

3.5 Solids entry into sewer system

3.5.1 Typical entry points

Solids can enter the sewer system at numerous entry points. Clearly an obvious solution to the problem of unwanted solids in sewers would be to simply block these entry points. This is not possible, because the toilet for example is intended as an entry point for matter to the system, but its abuse and/or incorrect use, results in unwanted solids also entering the system. Sanitary sewers, or separate sewers, have fewer entry points than combined sewers. In South Africa the places where unwanted objects can enter the sewers are:

- Toilet
- Shower and bath
- Bathroom basin
- Kitchen sink
- Gulleys (plumbing water collection points around the outside of a property)
- Manholes (where covers may be missing or broken)
- Construction sites (where objects are often discarded into open pre-commissioned sewers)
- Industrial or commercial facilities (including factories).

3.5.2 The toilet and solids entry

It is apparent from these reports that incorrect use of toilets contributes significantly to the entry of unwanted solids into the sewer system. This problem of inappropriate toilet use and rubble entering the sewer system is exacerbated in low cost housing areas. Govender, Barnes & Pieper (2011) provided an assessment on the physical living conditions of low-cost housing settlements in the City of Cape Town and the associated health conditions of the inhabitants. All sites in their study were older than 3 years, geographically representative of the City's low cost housing units and representative of the cultural groupings. The four study sites had distinct boundaries. Their household survey involved systematic random samples comprising 1080 persons living in 173 main houses and 163 shacks in the back yards of the same premises. It was reported that:

- 58% of toilets were non-operational at the time of visit;
- 26% reported cleaning their toilet once a week;
- None of the occupants knew how to fix a leaking tap or broken toilet;
- 64% of premises had blocked/overflowing drains; and
- 49% of yards were unclean and rubbish-strewn.

A questionnaire-based survey of 44 countries was undertaken by Ashley & Souter (1999) to determine what sanitary items were flushed versus binned. It was found that almost 75% of sanitary waste items found in sewers are flushed by women, and consist of tampons, applicators, sanitary towels, panty liners, cotton buds, cotton wool, condoms and toilet paper (Ashley & Souter, 1999; Ashley et al., 2004). Table 3-8 below indicates the disposal habits of the countries involved in that study. The totals do not add up to the number of countries, because in some cases the items were burned instead of them being flushed or binned. Burning these items was considered uncommon locally and thus was excluded from the table.

Table 3-8. Disposal habits for most common sanitary items (Ashley & Souter, 1999)

Number of disposals via	Sanitary Items	Condoms	Nappies	Toilet paper	Cotton buds	Disposable razors
Flushing	13	13	2	25	9	1
Binning	26	22	28	9	26	28

3.5.3 Contingent valuation to probe local toilet use habits

A consumer survey was also conducted in Stellenbosch as part of this project to assess toilet use habits, and in particular which solid waste items would be discarded by users into the toilet. Users indicating such disposal also perceived the action as being an appropriate method for discarding the particular waste item. The findings underline a clear lack of appropriate toilet use and need for improved toilet training. Table 3-9 presents a summary of the findings. Comments were added to the table for each item.

Table 3-9. Stellenbosch survey results – disposal of items in toilet

Description of solid waste item	Percentage of respondents who indicated that they would discard this solid waste item in the toilet		Comment
	Group A (Mainly students)	Group B (Low/middle income housing area)	
Newspapers & Magazine pages	8	28	Most common item for Group B: Used in place of toilet paper in low income area
Corn/Mielie husks	4	8	Used in place of toilet paper
Fruit & Vegetable peels	0	14	Ideal for composting; obvious incorrect toilet use
Wrappers, bags and packaging	8	16	Clear indication of incorrect toilet use in general
Nappies / Diapers	0	10	Various sanitary items are often discarded in the toilet, but are insoluble; it is not clear whether the toilet was an appropriate place to discard these items as alternatives are often not provided (e.g. bin or nappy dispenses near the toilet).
Tampons / sanitary pads	24	16	
Condoms	12	18	
Ear buds	32	10	Most common item discarded in toilet for Group A
Stockings	0	0	Stockings are often found clogging sewers based on site visits, but none were reportedly discarded in the toilet
Hair extensions	4	8	Obvious incorrect toilet use noted
Material and rags	0	4	Obvious incorrect toilet use noted
Metal pieces / cans	0	2	Obvious incorrect toilet use noted
Building material	4	4	Obvious incorrect toilet use noted

3.6 Solids handling and removal from the flow stream

3.6.1 Decentralised solids removal

Various technologies are available for removing solids from sewers. Two alternative philosophies are available as mentioned briefly earlier in this report, namely to remove solids at pump stations, or at the WWTP. This component of the work investigated the case where solids are removed at relatively small pump stations by means of screening baskets. However, this method requires regular maintenance and that poses a new set of problems. The philosophy is to solve problems as they occur and not wait for problems to increase the intensity further downstream. This is considered to be the proactive approach.

This chapter provides detail regarding solids in sewers, and addresses the handling, removal and composition of solids in the waste stream. It does not address the chemical or micro-biological composition of such solids.

The current literature review confirmed a report by De Swart & Barta (2008) that the majority of literature available about solids and overflows pertains to combined sewer systems (CSS) although South Africa has been implementing separate sewer systems (SSS) to provide waterborne sanitation and storm water systems to provide urban stormwater drainage. This chapter addresses published matter relating to both SSS as well as CSS where they were both considered applicable to SSS.

3.6.2 Solids handling ability of pumps and the need for removing solids

Pump manufacturers develop pumps capable of pumping solids. Nevertheless, unwanted objects reduce the lifespan of these pumps as they are not intended to regularly handle the type of unwanted solid objects found in sewers. Some sort of a screening mechanism to remove the solids upstream of any type of pump is useful. Pumps can only handle solids as per the relevant design specification – larger objects will lead to clogging of the pump intake. Preliminary treatment of sewage is needed to remove constituents such as sticks, grits, rags, floatables and grease that may cause operation and maintenance problems (Metcalf & Eddy, 2003). Screens can remove many types of solids that are larger than the pump can handle. There is a great need for robust pumps in informal areas. The desirable alternative would be to reduce larger objects to an acceptable size before pumping.

Even though screening activities constitute a relatively low technological component within the greater wastewater system, their importance as the primary defence against pump damage should not be underestimated.

3.6.3 Solids removal

In an earlier project progress report (Deliverable 3) it was noted that some sewer pump station components required further definition in addition to what given in previous research reports. The main linguistic ambiguity was around the terms used for the devices used to remove (or shred) solids in the sewage stream. These included rakes, bars, screens, traps and baskets.

For the purpose of this study it was necessary to define a term to describe all these devices generically as follows:

- solids handling device (SHD): any device used in a sewer system to remove solids from the sewage stream (e.g. screens and baskets), or employed for the purpose of reducing particle size so as to aid the solids moving further along the stream (e.g. macerators); a SHD is also known as a solids removing device.

Based on the site visits, most sewer pump stations were found to be equipped with some type of SHD upstream of the pump impeller. Grit removal systems are addressed separately in this chapter. It should also be noted that alternative methods such as grease traps are needed to rid the sewers of FOG products.

The CSIR (2003) gives only a brief guideline regarding screening at pump stations: "Adequate protection, where necessary, in the form of screens or metal baskets, should be provided at the inlets to pump stations for the protection of the pumping equipment."

Gross solids or screenings are sewage-derived materials larger than 6 mm (Gouda et al., 2003), are typically removed by bar screens or bar racks. They are debris consisting of rags, plastic, cans, rocks and similar items (Water Environment Federation, 2008).

Technology used to remove solids can be measured in terms of cost, degree of labour and effectiveness. Inexpensive technology is dependent upon a high manual labour content. On the other hand expensive technology could mean improved effectiveness and reduced dependence on manual labour. This section only addressed the SRSs available and how they operate. The various SRSs are used for different installations depending on the price, type of solids, type of area and space available. Using a SRS at sewage pump stations increases the lifetime of the pumps used, even if the advanced solids handling pumps are installed (Worthington-Smith, 2011).

3.6.4 Screens

Screens are generally divided into two main types, coarse screens and fine screens (Metcalf & Eddy, 2003). Cleaning can be done either mechanically, for large scale screens or manually for small screens on a daily or weekly basis depending on the flow rates. Screens at treatment plants catch about 15 to 35% of the total mass of solids entering the treatment plant (Ashley et al., 2004). Screen types can be described as shown in Figure 3-2.

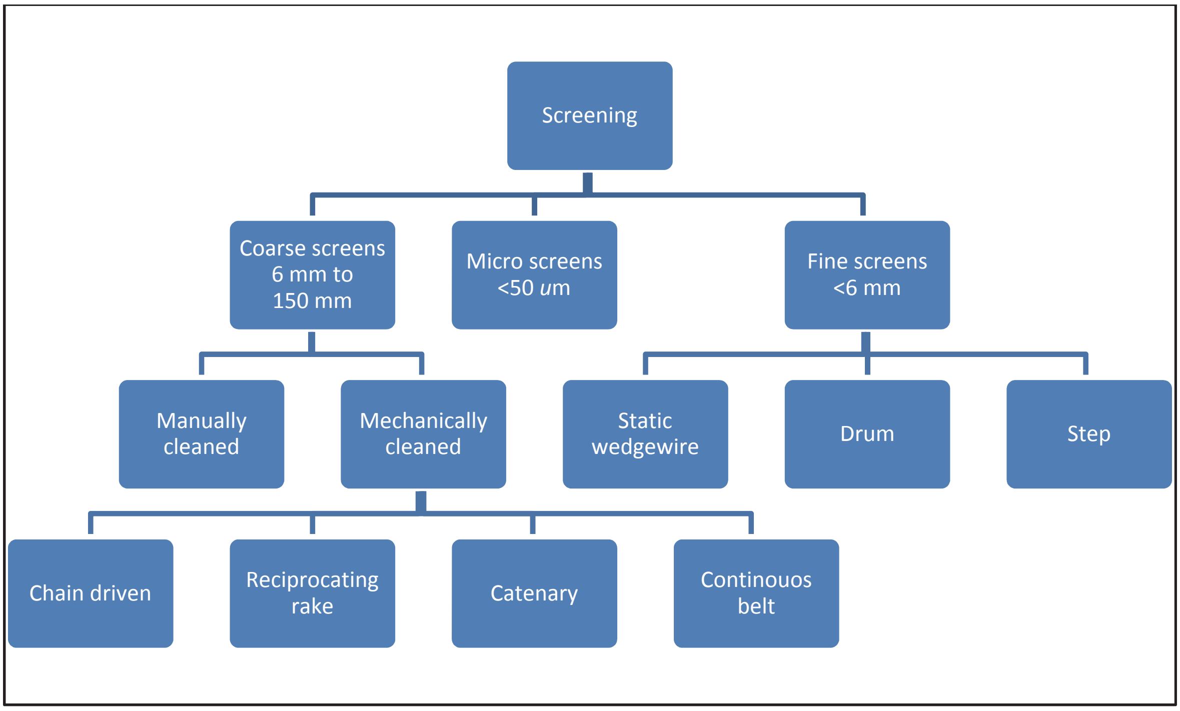


Figure 3-2. Types of screens used (adapted from Metcalf & Eddy, 2003)

Coarse screens have openings of 6 mm or larger and include manually and mechanically cleaned bar screens that remove large solids such as rags and debris. Nozaic & Freese (2009) classified screens as depicted in Table 3-10.

Table 3-10. Screening device classification (Nozaic & Freese, 2009)

Screening Device Classification	Size Classification	Size Range of Screen Opening
Bar screen		
Manually cleaned	Coarse	25 –50 mm
Mechanically cleaned	Coarse	15 – 75 mm
Fine bar or perforated coarse screen (mechanically cleaned)		
Fine bar	Fine to coarse	3 – 12.5 mm
Perforated plate	Fine to coarse	3 –9.5 mm
Rotary drum	Fine to coarse	3 –12.5 mm
Fine Screen (mechanically cleaned)		
Fixed parabolic	Fine	0.25 – 3.2 mm
Rotary drum	Fine	0.25 – 3.2 mm
Rotary disc	Very fine	0.15 – 0.38 mm

Some pump station or WWTP operators make their own improvised screens to work as is best for their needs. No screens are perfectly retentive (Ashley et al., 2005). The screens are often manually cleaned, but automated mechanical systems are also available. Mechanically cleaned screens are mostly used at installations with high incoming flows, such as major pump stations and WWTPs. Metcalf & Eddy (2003) describe different types of mechanically cleaned coarse screens, including front-cleaned, front-return chain driven; reciprocating rake; catenary; continuous belt types.

Fine and micro screens are typically used at WWTPs for primary clarification instead of primary sedimentation tanks (Nozaic & Freese, 2009). For the purpose of this study they are not addressed in further detail.

3.6.5 Baskets

Published work on baskets used to remove screenings is limited. During site visits it was found that baskets were based on simple designs which required regular maintenance. Baskets can be square, rectangular or circular depending on the shape of the sump or screening manhole. Of all the methods used to remove solids from the wastewater stream, it was noted that baskets were the device with the least literature available. The lack of knowledge on this led to some experimental testing of this screening device. This experimental testing is presented in Chapter 5 of this report. Two typical basket shapes are circular and square, seen in plan view.

3.6.6 Macerators

Macerators, also referred to as grinders are mechanical devices used to grind the solids to a smaller size, but are relatively expensive (Hanson, 2011). Operators using macerators need training and experience as they are dangerous and should be operated with. Macerators would be installed in areas where it is essential to reduce the solid size. Macerators are installed in a channel and their teeth grind the larger solids to a size small enough to be handled by the pump. Vesilind (2003) tabulated a variety of screens and macerators, as presented in Table 3-11. Due to the relatively high cost very few of these devices are used at small pump stations in South Africa.

Table 3-11. Variety of screens and macerators (Vesilind, 2003: 42)

Item	Range	Comment
Trash rack		
Openings	38-150 mm	Commonly used on combined systems – opening size depends on equipment being protected
Manual screen		
Openings	25-50 mm	Used in small plants or in bypass channels
Approach velocity	0.3-0.6 m/s	
Mechanically cleaned bar screen		
Openings	6-38 mm	18 mm opening considered satisfactory for protection of downstream equipment
Approach velocity (maximum)	0.6-1.2 m/s	
Minimum velocity	0.3-0.6 m/s	Necessary to prevent grit accumulation
Continuous screen		
Openings	6-38 mm	This type of screen effective in the 6- to 18 mm range
Approach velocity (maximum)	0.6-1.2 m/s	

Item	Range	Comment
Minimum velocity	0.3-0.6 m/s	
Allowable head loss	0.15-0.6 m	
<u>Comminutor (size reduction only)</u>		
Openings	6-13 mm	Opening a function of the hydraulic capacity of unit
<u>Grinder (size reduction only)</u>		
Openings	6-13 mm	
Typical head loss	300-450 mm	In open channel

3.6.7 Grit removal

Grit is defined as small heavy particles or coarse inorganic matter, like sand and gravel (Water Environment Federation, 2008). The composition of grit removed from sewers was studied by Nozaic and Freese (2009), who reported grit to comprise of sand, eggshells, bone chips, seeds, coffee grounds, and large organic particles, such as food waste. Heavier metallic particles are less common, but may also be present. Occasional peak flows should flush the system and prevent serious blockage in the sewers due to the accumulation of grit alone (Merritt, 2009).

Removal of grit is done with sand traps, grit chambers or degritters, all of which use sedimentation-principles to remove the grit. Sedimentation of grit can occur in pipes and sumps if infrastructure is not well designed or constructed. The ideal is to keep the grit moving along the sewer pipes and then to remove it from the system at pump stations or at the WWTP.

Ashley et al. (2004) reported that knowledge regarding sediments in sewers was limited. Although some later reports on the topic could be traced during this literature review it is evident that the knowledge remains relatively limited as far as sediment in sewers is concerned. Grit could be removed at sewer pump stations, and site-visits during this study confirmed that this was done in places. In the Western Cape the problem of grit in the system is relatively common. Low-income areas tend to have more problems with sand deposition, as houses are built in sandy areas and streets are often not paved. Sand entry in Western Cape sewers is a significant problem, especially in the Cape Flats (Loubser, 2011).

Sand traps and degritters are mechanisms designed to remove grit. Both these take advantage of gravitational and centrifugal forces to allow for sedimentation. Sand traps and degritters use slow flow velocities to induced sedimentation (Metcalf & Eddy, 2003). The sand trap is usually a long channel through which the sewage is conveyed at a reduced velocity so that the heavier particles sink to the bottom. Degritters are circular in shape to induce a swirling motion. Centrifugal forces cause the heavier particles to settle so that they can be removed from the system.

3.7 Solids behaviour in typical sewer baskets

3.7.1 Experiment with selected solids

The site visits and literature review conducted indicated a specific lack of knowledge regarding solids in local sewers, and in particular the use of screening baskets to remove solids at sewage pumping stations. Despite this these baskets were found to be relatively commonly used. This led to the idea of including experimental testing of a subjectively selected screening basket in the project scope.

The research involved a full scale laboratory model in a controlled environment to assess various parameters influencing the use of screening baskets and their effectiveness in catching various types of debris. Subsequent to the tests the idea was to develop an efficiency index for screening baskets, based on fuzzy logic methodology that could be used as a component of the pump station problem decision support tool.

The laboratory experiment was built to investigate the current use of baskets to remove solids at pump sumps. The focus was on relatively small pump stations. Theart (2011) confirmed that baskets were frequently built for pump stations and mentioned Zwangavho Trading as one firm constructing such baskets for the local municipal market. Reference was made to baskets in some local publications such as the CSIR (2003) and van Vuuren & van Dijk (2011). The intention with this limited laboratory experiment on selected unmixed solids was to gain knowledge of basket performance and to identify future research needs.

It immediately became apparent that the level (height) at which the basket would be operated in relation to the surface of the fluid in the sump was a major influence in how much debris could be trapped. Site-visits suggested that the height at which baskets were located in practice varied appreciably from one pump station to the next. At some installations the basket was beneath the water surface and at others above the surface level. This was further influenced by the on and off settings of the pump sump level. In some instances the basket always remained above the water level, while in others it remained submerged. Testing the impact of the basket level in relation to the water surface level was one of the main focuses of the laboratory experiments.

Two variables were chosen for the experiment, the retention time of the solids in the water (retention time) and the height of the basket above the liquid in the sump (basket height). All other parameters remained constant throughout the testing in the controlled environment.

The key aims of the experiment were to evaluate the following:

- The basket behaviour at different operating heights in relation to the liquid surface level;
- The efficiency of the basket in catching certain predetermined solids; and
- The efficiency of the basket with certain predetermined solids at different retention times.

The design of the experiment was based on findings during field visits to actual operating installations. The experiments had certain limitations so assumptions were made to evaluate the basket's efficiency. The assumptions made are presented in Table 3-12.

Table 3-12. Assumptions for laboratory experiment

Assumptions	Motivation
160 mm pipe was used (150 mm inside diameter)	Most common (found during site visits)
Velocity between 0.7 m/s and 2.5 m/s	Standards for self-cleansing sewers (CSIR, 2003)
Slope must be steeper than 1:200 (this will only give 0.6 m/s so slope should be steeper than 1:150 if 0.7 is the criteria)	Minimum sewer gradient (CSIR, 2003; van Vuuren & van Dijk, 2011)
Basket tested at two heights	Predetermined
Solids tested at two different retention times	Predetermined
Constant flow conditions	In order to limit the number of variables to suit the available pump capacity in the laboratory

3.7.2 Experimental design

The basket used in the tests was based on a typical square basket installation in a manhole. The basket used in the laboratory experiment had 50 mm openings on the recommendation of Theart (2011), the manufacturer of the screening basket, since it was considered to be typical of what was manufactured for use in the Western Cape. The experiment was done with a full scale model.

The experiment was conducted in the hydraulics laboratory of Stellenbosch University. The space was required was 5 m x 3 m. The key requirements in terms of the experimental design were that the pipe slope had to be steeper than 1:200 and the resulting flow velocity between 0.7 m/s and 2.5 m/s. Manning's equation was used to determine the velocity in the pipe.

A Manning roughness coefficient of 0.013 was selected for the plastic pipe with an inside pipe diameter of 150 mm. Before construction of the experiment the angle of the slope was determined as 1:40 with a corresponding full flow velocity of 1.36 m/s which met the requirement of being more than 0.7 m/s and less than 2.5 m/s. This would also occur for the flow depth equal to 50% of pipe diameter.

However, after construction the slope was 1:43, for which a velocity of more than 0.7 m/s and less than 2.5 m/s was present for the flow depth used.

The following values were applied to all the tests in the experiment:

D = 0.15 m (inside diameter)

n = 0.013

S = 1:43

y = 0.035 m (depth measured during tests).

These values were substituted into the equations as mentioned above and the following was calculated:

A = 0.0052 m^2

P = 0.15 m

θ = 1.008 radians

v = 1.24 m/s.

These values were consistent for all tests and they met the necessary requirements to simulate a typical pump station sump inflow set-up. The flow was measured during tests and the velocity remained constant at approximately 1.2 m/s for all tests. In order to perform a full scale experiment the following components were required:

- Water supply
- Inlet pipe
- Sump
- Basket
- Hoisting equipment (pulley system)
- Solids to test.

A 3000 litre rainwater tank was used as a sump. An outlet pipe of the same size as the inlet pipe was inserted into the tank to ensure that the water level remained constant. In this way the surface level of the liquid was controlled relative to the basket's submerged depth. A typical square basket with openings of 50 mm was used.

The experimental design was drawn in AutoCAD (2D) and Inventor (3D). Figures 3-3 to 3-5 illustrate the dimensional details of the top, side and front views respectively and Figure 3-6 presents the 3D view. The actual model is shown by the photo given in Figure 3-7.

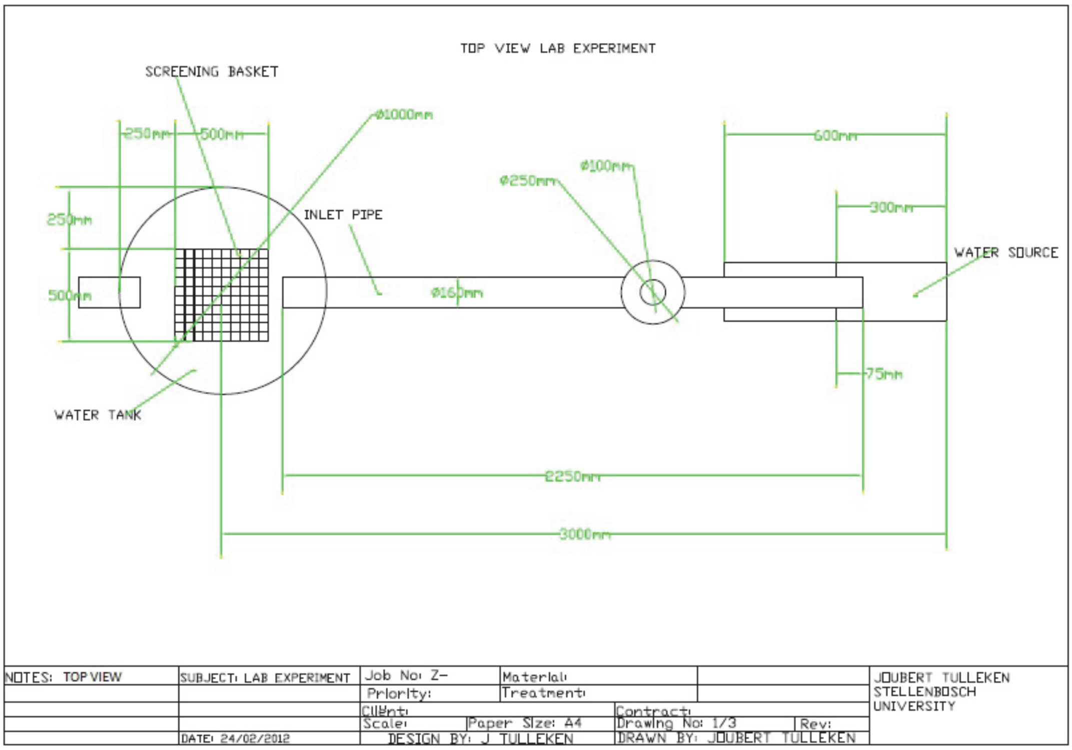


Figure 3-3. Top view of lab experiment

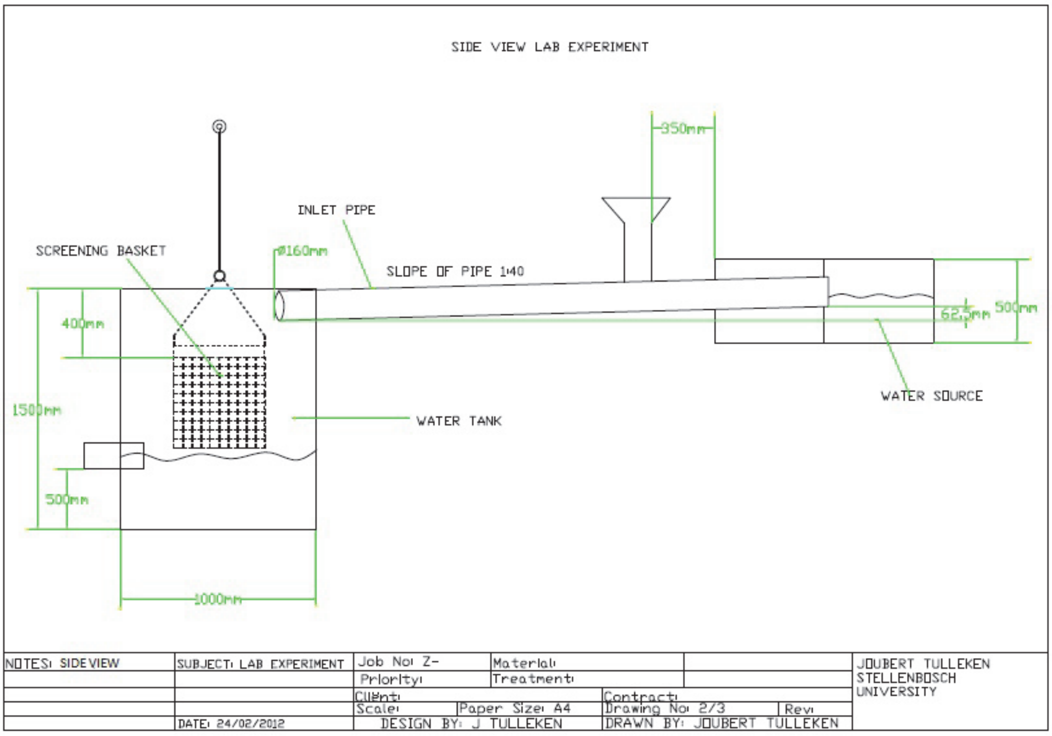


Figure 3-4. Side view of lab experiment

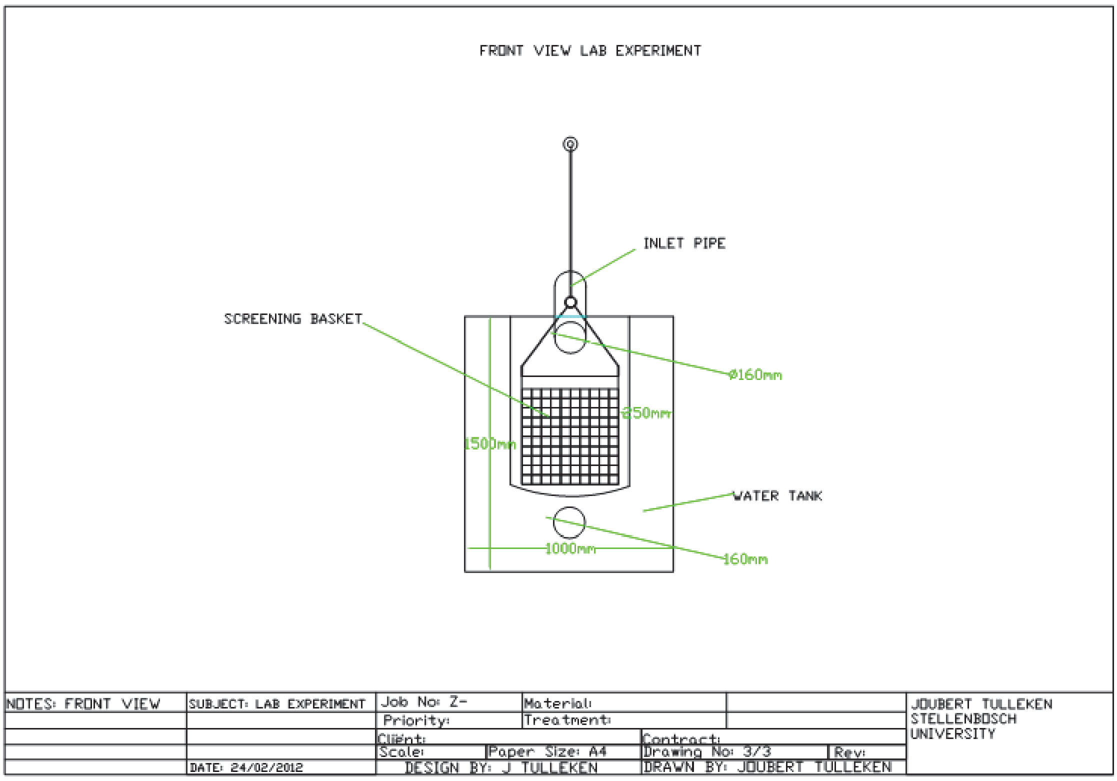


Figure 3-5. Front view of lab experiment

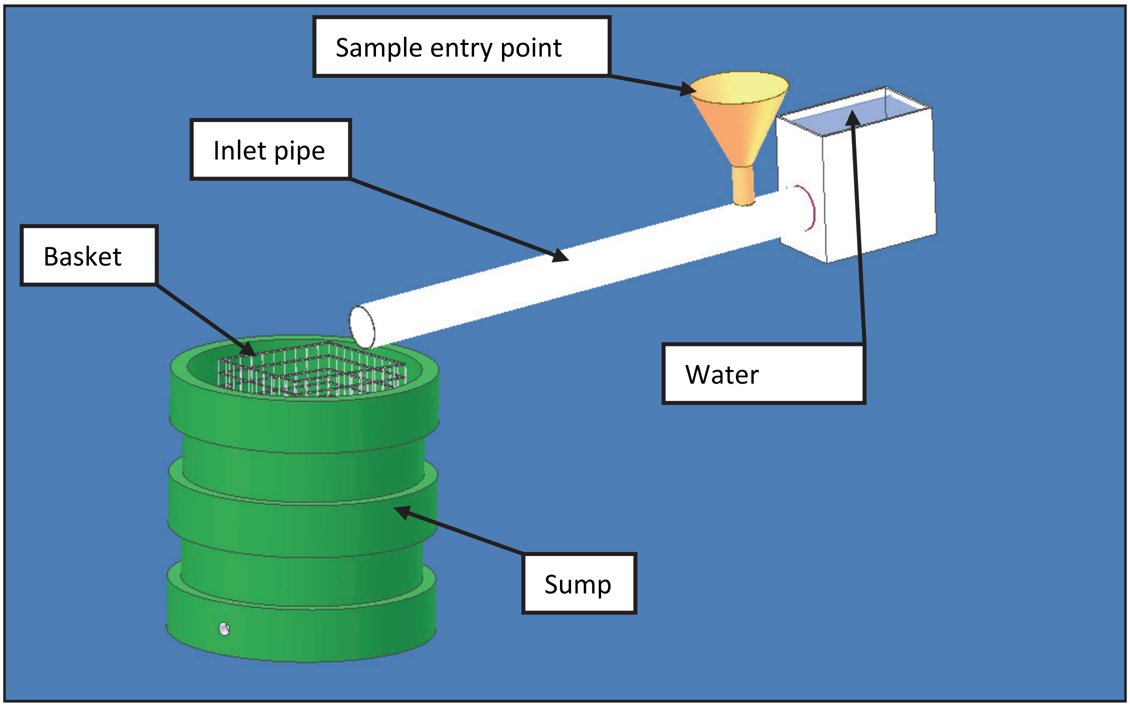


Figure 3-6. Three dimensional view of laboratory experiment

Figure 3-7. Actual model in laboratory

3.7.3 Testing phase

The laboratory tests took approximately four weeks to complete. For the purpose of the experiment water was used as a proxy for the main wastewater stream, prior to adding the respective solids to the flow in the pipe. All the tests were done with the retention time of the solids and the height of the basket top above the water surface as the two variables. All solids were tested at 0 hours and 1 hour retention time. The basket was tested at a height above the water and halfway submerged in the water. The test for each type of solid product was repeated five times, for each scenario. The following four scenarios were tested:

- Solids at 0 hours retention time with top of basket above water;
- Solids at 0 hours retention time with top of basket halfway submerged in water;
- Solids at 1 hour retention time with top of basket above water; and
- Solids at 1 hour retention time with top of basket halfway submerged in water.

When the top of the basket was above the level of water in the sump, the flow would fall from the pipe exit directly into the basket at a specific location determined by the flow rate and basket set-up. The flow stream was typically large enough to impact some of the basket's steel bars (as is evident in the photos of tests presented later in this chapter; e.g. Figure 3-10).

No attempt was made to vary or control the position where the water stream would impact the basket. When the top of the basket was halfway submerged, the position of the water stream relative to the basket was irrelevant, because the solid matter would disperse after impact in the pool of water, prior to hitting the basket edge at some point.

3.7.4 Solids tested

A total of 6 different solids were tested. The selected solid products are presented in Table 3-13 with a brief note on the motivation for each solid in the experiment. Steyn (2011) and Trautmann (2011) reported that consumers in low income areas use various products for sanitary purposes other than toilet paper. This was the main motivation for testing newspapers and magazine papers. Ashley et al. (2005) and Gouda et al. (2003) found that cotton buds (ear buds) were a notable problem and Crombie (2011) found this to be true for South African sewers. Stockings are a threat to pumps, as they stretch easily and have the potential to clog and tangle around shafts, or get caught by the impeller and could cause pump damage (Trautmann, 2010).

Table 3-13. Solids tested in experiment

Solid	Quantity tested in each test	Motivation
Toilet paper	250 g	Common sanitary item
Newspaper	250 g	Used for sanitary purposes in low income areas
Magazine paper (gloss)	250 g	Used for sanitary purposes in low income areas
Cotton buds	100 buds	Reported to be a problem item
Dental floss	50 pieces of 0.5 m each	Sanitary item with potential to easily clog; typically discarded in the toilet
Stockings	10 pairs	Reported to result in pump problems (clogging of screens and baskets; clogging pump inlets; winding around shafts)

A few photos of the products selected for tests in the laboratory experiment are shown in Figure 3-8.

3.7.5 Method

The products tested are referred to as samples. Samples had to be prepared before they could be tested. Samples were inserted at the top of the inlet pipe as shown in Figure 3-6. All the products were inserted into the model one by one. This took approximately 3-4 minutes per test to ensure that the products did not tangle before hitting the basket. Samples were then left in the basket for 1 minute after the last item had been added. This allowed sufficient time for the items to either get caught by the basket, or pass through the basket. The samples caught by the basket were then removed, counted or weighed in order to obtain representative results. Samples passing through the basket were caught in a screen to prevent them from entering the laboratory water storage tanks.

A total of 100 samples were tested. Cotton buds and stockings did not need any preparation. All paper products (newspaper and magazine paper) were cut into A4 size and then folded twice before being entered into the model, in line with what was considered typical when these were used to replace toilet paper. The dental floss was cut into 0.5 m meter lengths. Toilet paper was folded three to four times to form a presentable sample.

Figure 3-8. Products tested: a) toilet paper; b) newspaper; c) magazine paper; d) cotton buds; e) dental floss; f) stockings.

All samples tested at 0 hours were first wetted before being entered into the model, which was done by dipping the product into a bucket of water. All the samples tested after 1 hour retention time was left in the bucket of water for a period of 1 hour prior to testing. The samples were stirred every 5 to 10 minutes so simulate the movement they would experience when flowing through pipes. A period of 1 hour was chosen to be consistent, although in practice the retention time for every drainage area would differ depending on the basin lag time. The 0 hours retention time would represent a home just upstream of a pump station; the product would not have time to dissolve or increase in size due to water absorption. The worst case scenario for the pump station would be the solids that enter the network just before the station, as illustrated in

Figure 3-9. The sewage leaving area 1 would reach the pump station almost immediately while sewage coming from area 4 would take longer to reach the pump station.

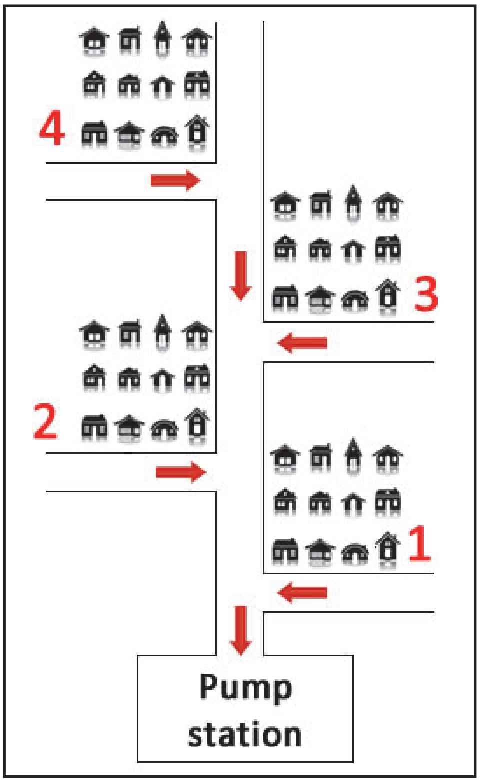


Figure 3-9. Typical sewer system schematic

All samples were weighed or counted before they were inserted into the model and the quantity caught by the basket was also counted or weighed. All samples that had to be weighed were dried at room temperature for a period of two weeks, thus simulating a stockpile of solid waste that would be removed by road from the pump site each two weeks.

For tests where the basket was above the water surface the basket was placed just below the inlet pipe, as shown in Figure 3-10. The surface of the water was a distance of 650 mm below the inlet pipe.

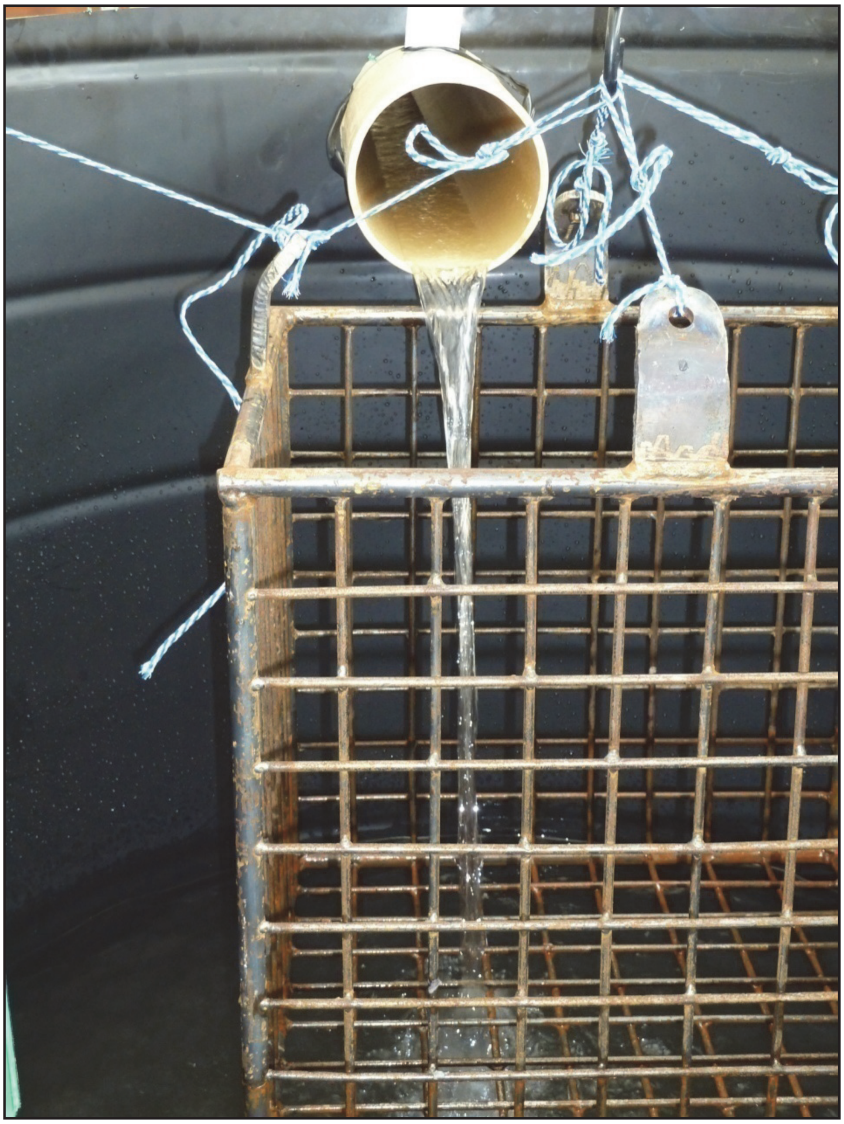


Figure 3-10. Experimental setup showing inlet pipe and clean basket

3.7.6 Limitations

The results of the experiment are considered to be case specific and only directly applicable to the particular set-up. The knowledge gained would hopefully give insight into basket use and would identify problem items with the potential to clog the basket, or pass right through it.

Based on the subjective judgement gained by conducting the tests, a list of factors was compiled that may impact on the results presented, based on the set-up in this study:

- Diameter of inlet pipe
- Flow velocity and flow rate (especially for the basket above the water level)
- Different operating conditions
- Distance water falls before entering the basket
- Basket size relative to manhole or pump sump wall (clearance between basket outside edge and sump inner wall)
- Mixing of products; addition of grit and/or FOG

- Orientation of the basket
- Size and quantity of samples used
- Size of basket openings
- Size of the basket
- Slope of inlet pipe
- Time basket stays in water
- Time samples stay in basket
- Type of sewer system (e.g. solids free)
- Use of actual sewage instead of water
- Whether a pump in the sump would be operating or not.

3.7.7 Results

For baskets to work efficiently they should allow the passage of paper products, which are pumpable. The basket should only catch solids that could damage the pump and the rest of the sewage should be kept in motion and pumped away. In this way the basket would not fill-up too rapidly with products that could be pumped away.

The results are presented in the following sections, and are discussed for each product separately.

3.7.8 Toilet paper

Toilet paper was only tested once, because it was clear that the basket did not catch any of it. The toilet paper disintegrated as soon as it hit the basket. This shows that toilet paper disintegrates in the waste stream as would be expected. A total mass of 250 g of the product was disposed of in the waste stream entry point, but only 8 g was caught by the basket, as illustrated in Figure 3-11. Toilet paper was not tested again, because it was clear that it disintegrates and the result of the one test was considered sufficient. The conclusion was that toilet paper would not be caught by baskets, clog baskets or damage pumps.

Figure 3-11. Toilet paper caught by basket

3.7.9 Newspaper and magazine paper

Newspaper and magazine paper showed more or less the same results, therefore they are addressed together in this section. For both these products most items were caught by the basket at 0 hours with the basket above and below the water as illustrated with the graphs in Figure 3-12 a&c and Figure 3-13 a&c. This indicates the both these paper-based products would quickly block the basket. If these papers were used instead of toilet paper baskets would fill too quickly, and would require increased maintenance. However, this is the worst case scenario where the products would enter the sewer system just before the pump station, as illustrated by zone 1 in Figure 3-9, before becoming saturated.

After being in the water for 1 hour, less of the product was caught, but it was clearly still a problem when compared to toilet paper. The average amount of newspaper caught after 1 hour retention time was 149.6 g and 166.8 g of 250 g, respectively for the basket above the water and for the basket halfway submerged. For the magazine paper the average caught after 1 hour retention time was 145.2 g and 158.8 g respectively for the basket above and for the basket halfway submerged. The baskets caught slightly more of the newspaper than the magazine paper after 1 hour retention time for both heights as presented in Figure 3-12 b&d and Figure 3-13 b&d. This is probably because the magazine paper has a glossy finish. The basket caught slightly less of the products when it was suspended above the water. This result should not be evaluated out of context, since when the basket was halfway submerged the product that escaped the basket would rotate in the sump and was caught on the outside of the basket. However, if the product remains in the sump for a longer period it may settle to the bottom, but this would be a function of the clearance between the basket and sump side. Figure 3-14 illustrates the newspaper and magazine paper caught by the basket in different scenarios.

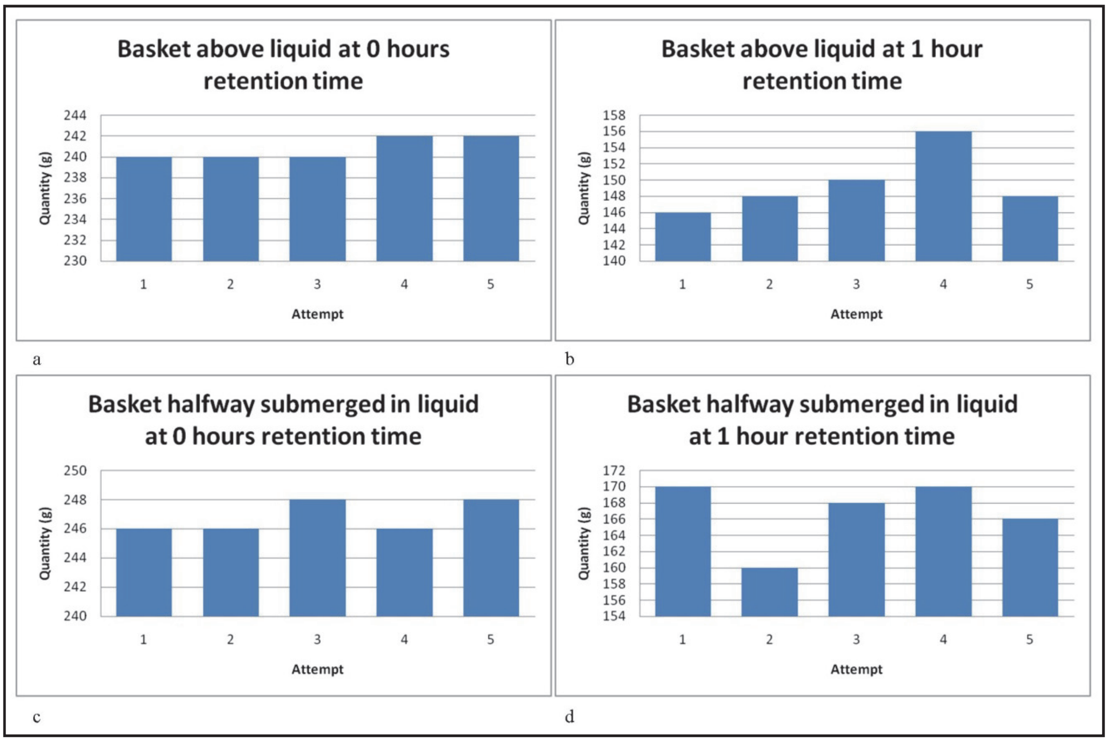


Figure 3-12. Newspaper test results

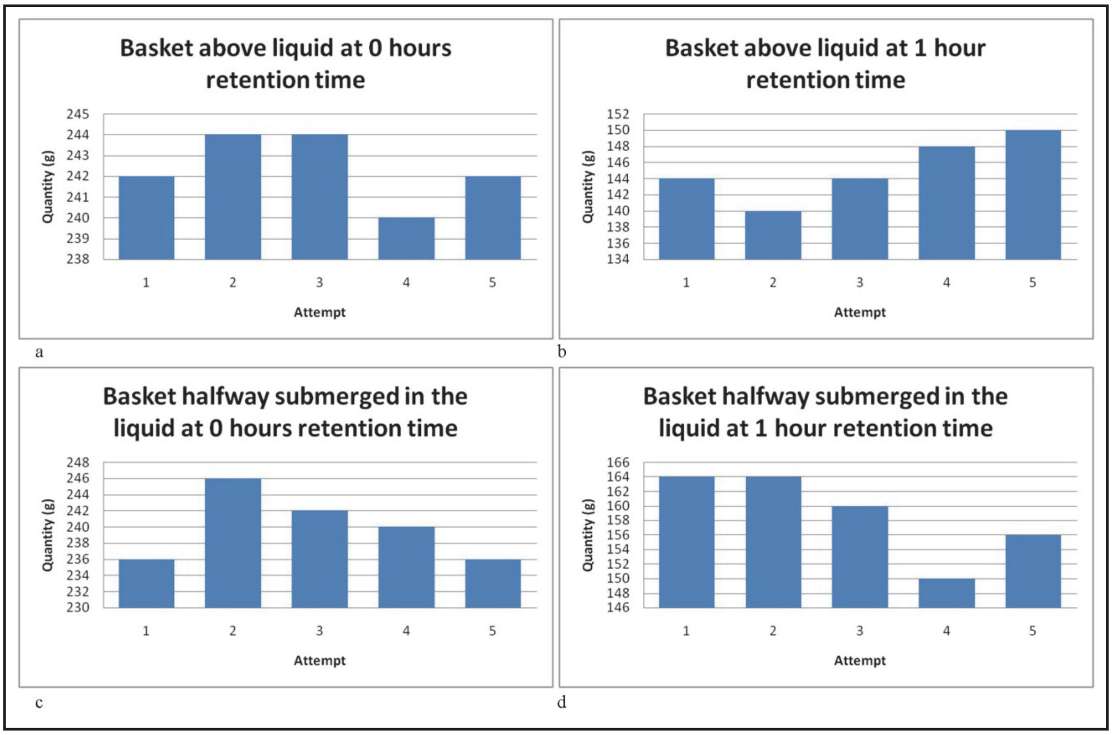


Figure 3-13. Magazine paper test results

Figure 3-14. Newspaper and magazine paper caught by basket

3.7.10 Cotton buds

Cotton buds were reported to be are a major problem and were thus included in this study. It was hoped that they would be caught by the basket, but common sense suggested that the particular basket grid was too course to do so. As expected the basket used during tests did not remove them effectively due to the screen spacing of 50 mm. Finer spacing would be required to catch cotton buds, but would obviously clog and fill up even sooner with the other products.

When the basket was suspended above the water, the basket caught virtually nothing. With the basket halfway submerged it caught slightly more cotton buds with 0 hours retention time. The basket caught about 21% of the cotton buds on average for the basket submerged after 1 hour retention, as seen in Figure 3-15d. This was due to puffiness of the cotton end of the buds after being in the water for 1 hour. The buds were then more likely to get caught, especially if they are swirling around in the sump while the basket is still submerged. The results of this test are presented in Figure 3-15.

Cotton buds pose a problem for sewers, because they have a rigid plastic structure and are not biodegradable. New biodegradable cotton buds are available that have paper stems and sink, where the plastic-stemmed cotton buds initially floated. The stems of the biodegradable buds lose their rigidity after being in the liquid for a while, but they also are not effectively removed by the basket. Figure 3-16 shows the two types of cotton buds and photos of the tests for the plastic-stemmed cotton buds.

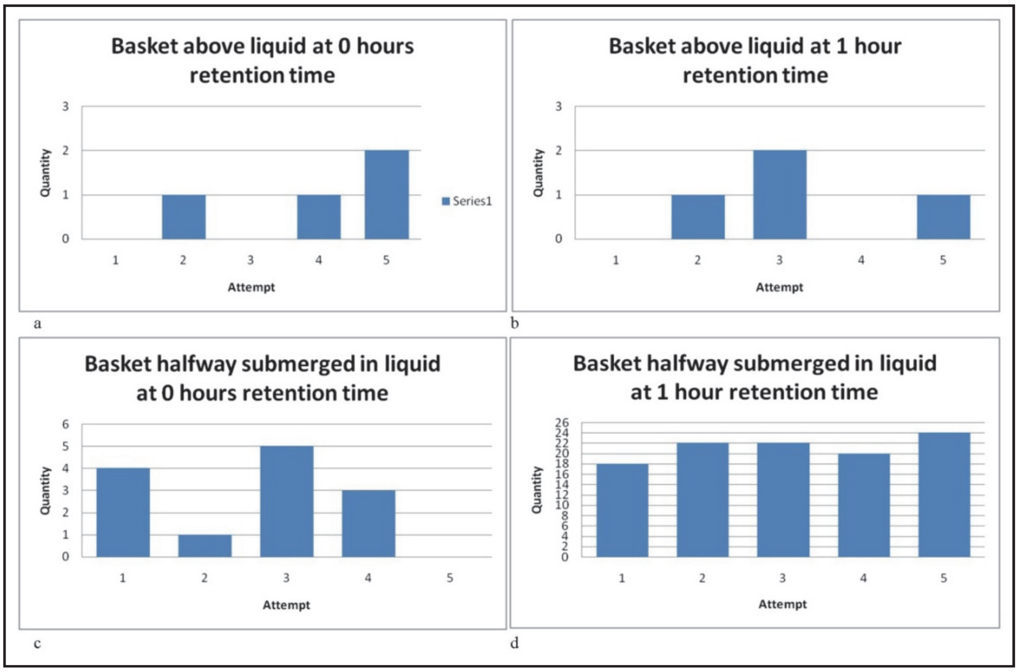


Figure 3-15. Results for cotton buds (not a biodegradable product)

Figure 3-16. Types of typical cotton buds showing "puffy" cotton ends.

3.7.11 Dental floss

The results presented in Figure 3-17c&d indicate that dental floss is almost always caught if the basket is halfway submerged in the water. The results for the basket above the water after 1 hour retention were inconsistent, but on average it caught more of the sample than for 0 hours retention time for the same height. Figure 3-18 presents photos of the results.

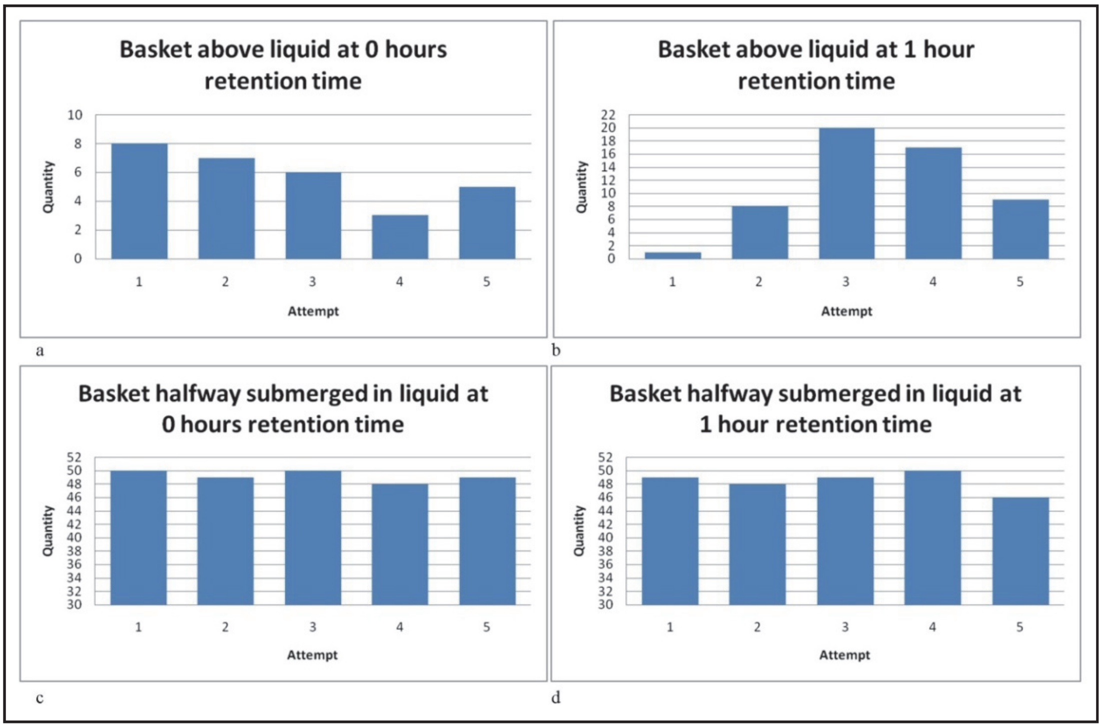
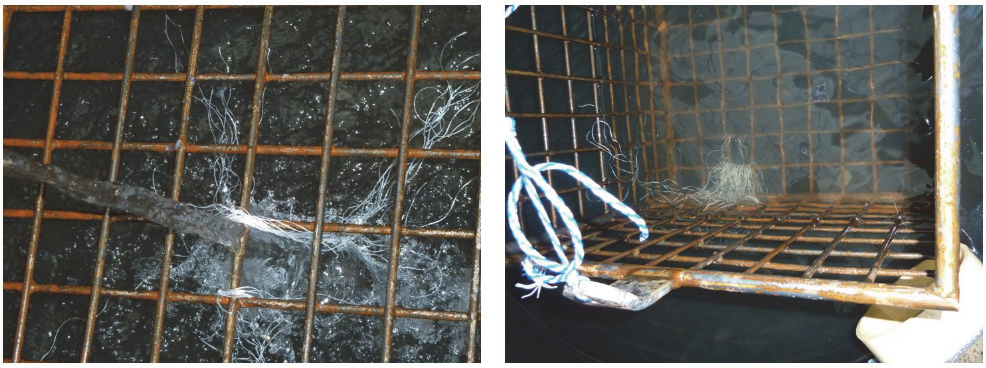


Figure 3-17. Results for dental floss



Dental floss 1h, basket above — Dental floss 0h, basket submerged

Figure 3-18. Dental floss caught by basket

3.7.12 Stockings

The stockings were all caught in all tests. The pictures in Figure 3-19 show the stockings caught by the basket. It is not clear then why the field investigations led the team to understand that stockings would end up in the pumps' impeller. The deduction was made that baskets were not used in these problem-scenarios, or that they were not cleaned regularly, thus resulting in stockings passing on down the system to the pump.

Stockings after 1h, basket above — Stockings after 0h, basket submerged

Figure 3-19. Stockings caught by basket

3.7.13 Final tests with mixed products

Most of the results on the individual items indicate that the basket works better if it is halfway submerged, except for the paper products. In order to get a better result for the paper products two final tests were conducted to see if the paper would disintegrate or settle with time. This was done because baskets are not normally cleaned as soon as they are full, but according to reports from the site visits, they get cleaned maybe once or twice a day, at most. The paper products are also the only products with the exception of biodegradable cotton buds that could disintegrate into very small pieces.

A subjectively determined mix of typically products in the waste stream was selected, based on literature reviews and physical inspections during the site visits, as shown in Figure 3-20. All these were used in the same test. The plastic, metal and cloth products were placed in the system first and the newspaper and magazine paper last. The test was repeated twice, once with the basket suspended above the water and the other with the basket halfway submerged in the water. After the products had been inserted in the model the water was kept running for an hour. The water was then turned off and the basket was left overnight (15 hours). The next morning the water was turned on for another hour, after which the results were observed.

Figure 3-20. Selection of waste products for final tests

In each test almost all the non-paper products were caught by the basket. When the basket was above the water, almost all the paper products were caught as well. The paper also had a chance to dry overnight, so it did not dissolve easily when the water was turned on again (this would simulate a stream of water impinging the basket at different locations on the steel grid as the sewer flow rate varies diurnally).

When the basket was submerged, only a small amount of paper was caught and the rest disintegrated or settled to the bottom of the sump. This scenario would perform better in practice, because the basket would not fill up with paper-based products that could pass through the pump.

These tests are illustrated by Figures 3-21 and 3-22. Figures 3-21 a & b illustrates the basket above the water with the products. In Figure 3-21c the paper products remaining in the sump are visible under water on the sump floor. Figure 3-21d indicates the amount of paper products caught by the basket on the right and the products that passed to the sump floor on the left. If the basket were to be operated above the water, the paper products will soon fill it up.

Figure 3.21. Photo of final test products (basket above water)

Figures 3-22a & b illustrate the basket submerged halfway in the water with the products it caught. In Figure 3-22c the paper products remaining in the sump are shown; this represented more than half of all the paper in the test. Figure 3-22d shows the number of paper products caught by the basket on the right and the products that passed on the left. This proves that the ideal operating height would be when the basket was submerged in the water. The paper products get a chance to dissolve and settle, thus not filling the basket with solids that should otherwise be pumped away further downstream.

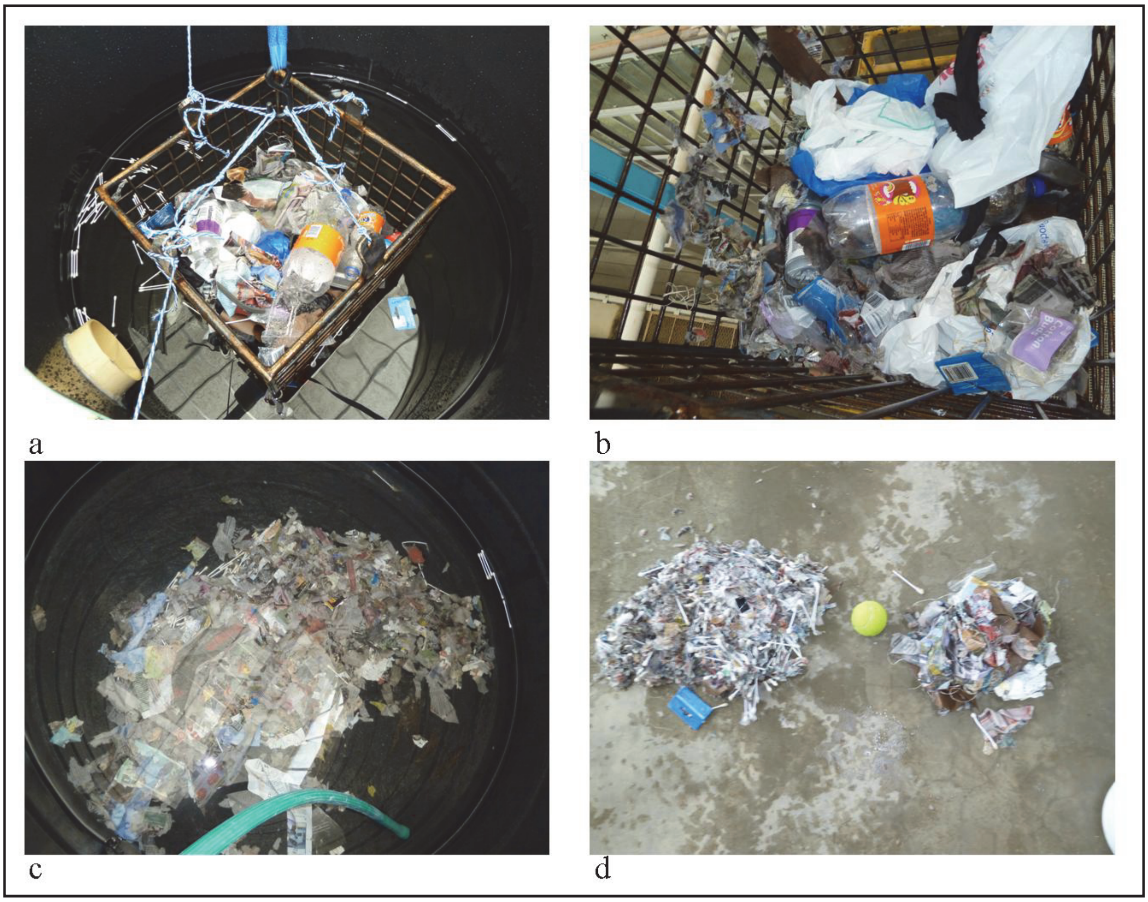


Figure 3-22. Photo of final test products (basket submerged halfway in water)

It is recommended that the operating height of basket be at the mean depth of the sump or somewhere between the on and off sump levels of the pump. By operating the basket in this way, paper products will be constantly exposed to the liquid in the sump, giving them more chance to dissolve and move on down the system.

As part of the final report the team intends to derive conceptual guidelines for regular maintenance of screening baskets, based on the tests and composition of solids in the sewer stream from former studies.

3.8 Main points

In summary the following main points were raised in this chapter:

- Sewers operate over a wide range of flow rates and the limiting values need to be taken into account when evaluating how effectively a sewer will transport solids to a pump station.
- Effluent velocity at the various flow rates is the most significant factor influencing the transport of solids through a sewer.
- A distinction needs to be made between the solids that can be transported through a sewer in terms of their specific gravity relative to that of the effluent, whether or not they will disintegrate with time and their impact on the operation and life of pumps.
- As the clogging of pumps by material that had a specific gravity similar to that of the effluent was a problem and little literature on the subject could be found, a series of laboratory experiments was done to determine the effectiveness of screening baskets in removing these materials.

- Recommendations for the location of screening baskets relative the effluent levels in the sump where they are to be placed were made and the need for further research in this regard was noted.

4. SYSTEM MANAGEMENT AND OPERATION

4.1 Cost implications

4.1.1 Overview

Operating and maintenance costs of sewer systems usually exceed the initial costs and should be factored into the decision making process. One aspect of doing this is to compare the total life cycle costs (LCC) of alternative pump and rising main configurations to determine the most cost effective solution (Dhillon, 2010). Bloch and Budris (2004) present useful reading matter on the reduction of LCC in the case of pumps specifically. They report that, despite the knowledge of better methods, most decisions are still made solely on the basis of the lowest initial purchase and capital cost. The typical LCC breakdown for pumps is presented by Bloch and Budris (2004) as 64% for energy requirements, 27% for maintenance and repair and only 9% for the initial cost.

4.1.2 Life Cycle Cost

The LCC of a pump system is the total amount of capital, installation, operating, maintenance and disposing costs of the equipment over its entire design life. LCC analysis can be used as a tool to compare possible configurations and to decide on the best economical solution. According to Europump there is great opportunity to optimise existing pump systems because of the ever changing water demand. Energy consumption and emissions in existing systems can be reduced by changes in the equipment used. Energy costs in pump systems normally dominate all of the other LCC costs.

The time value of money is an important factor in LCC analysis. Costs for maintenance, operation and energy usage of a pump are continuous throughout the pump's lifetime. In order to add these costs to the capital cost it must be discounted to its present values (Dhillon, 2010).

Much has been written in recent years about LCC in the water industry. For clean water pumping these calculations give meaningful results as energy consumption and maintenance requirements are very predictable. In the case of pumping wastewater it is relatively difficult to quantify all the associated costs. It is also not necessarily practical in the South African context to apply European principals as our sewerage is often of varying quality. However, operational and running costs are often not sufficiently considered when designing and evaluating these installations.

4.1.3 Capital cost

The capital cost of a pumping system depends on the size and type of the components it contains. The components in the system are interdependent as are the costs. The smaller the diameter of the pipe used in a system for a given flow rate, the bigger the pump and the more power required and the more expensive the installation becomes. There is thus a balance between the size, type and cost of all the components in the system. Capital cost is considered to be a once of item and depend on manufacturers' prices. Other considerations are the type of pump, whether it should be submersible or not and the rising main materials currently available at the specific location.

4.1.4 Energy cost and tariffs

One of the biggest contributors of the high operations and maintenance (O&M) costs is the high cost of electricity. Energy has become expensive when compared to historic rates for various reasons. The efficient usage of energy is particularly applicable in South African context due to the announcement from the National Energy Regulator of South Africa on various tariff increases.

Most of the major sewer pump stations in South Africa are owned and operated by local authorities or municipalities. ESKOM does provide a “night save” rate that could be implemented to save electricity costs, but peak flow times should be taken into account in the design and optimisation of a pump station and these do not necessarily correspond to the times at which the lower rates are applicable.

Energy consumption depends on the design of the system which includes the pump, the rising main, and other components such as valves and bends. All these are interdependent and should be carefully matched to ensure the lowest energy and maintenance costs. Europump (www.europump.org) notes the factors to consider how they function, interact and affect energy consumption and how understanding this will enable designers to reduce costs by optimising the energy efficiency of a whole system.

Another consideration, already mentioned, is the size and type of pipe used for the rising main as this has a significant effect on the energy requirements and future costs.

4.1.5 Maintenance cost

Although efficiency is an important factor, pump selection should also consider the effectiveness of operation and the associated maintenance costs and requirements. As part of life cycle management, the scheduling of routine and preventative maintenance actions in accordance with risk-based prioritisation is proposed as a key to minimising maintenance cost while maximising long term performance.(GLS, 2010).

Maintenance costs depend on the frequency of services, the price of parts and the cost of labour. The cost of spare parts can be obtained from the supplier’s invoice, although this is not always practical for many local service providers and labour costs can be determined from timesheets, job tickets or work orders

A maintenance program ideally should include frequent minor services as well as less frequent major services that are prescribed by the pump supplier. A major service would typically require that the pump be removed from site and serviced at the manufacturer’s premises, while a minor service could be conducted by operational personnel. The time intervals of major services should be based on a pump’s operating hours before failure. This could be difficult to predict if no records are kept, but a value could be estimated by taking the mean time between past failures and knowledge gained from experience.

Regular maintenance should include lubrication, alignment and balancing of pumps plus pipe maintenance.

4.1.6 Operating cost

The frequency and type of labour activities associated with the operation of the pumping system determines a significant portion of the operating cost. Sewer and solid handling pumps would generally require more supervision than clean water pumps due to blockages. Condition and performance monitoring and preventative maintenance activities should also be considered as an operating cost.

When monitoring the pump, the hydraulic performance of the pump, the operating temperature and vibration should also be measured.

4.2 Optimisation of pump-pipe systems

Energy consumption at pumping installations is an ever-increasing concern, as was noted decades ago internationally (Walski, 1980; Daffer and Price, 1980). It is of particular concern in South Africa, as was noted by Osry (2006), and has become even more so in the light of the recent spate of power failures.

Pump-pipe optimisation based solely on capital cost would give an inaccurate result, as a relatively large proportion of the total life cost for this part of the system is due to operation and maintenance costs, including energy consumption. Clearly computer modelling is essential to optimise a system (Lackowitz and Petretti, 1983). A number of international publications have presented methods for optimising pump selection for water distribution systems (Aldworth, 1983; Clingenpeel, 1983; Pulido-Calvo et al., 2006) and pump suppliers offer various advanced yet subjective software suites for pump selection. Despite this knowledge many South African studies are based on simple "guideline" principals, often neglecting the critical LCC of the energy-hungry system components. The optimisation of sewer pumps and their sustained efficiency over their life span is often complicated by other factors when comparing them to potable water pumps.

From a strategic perspective sewer pump stations form only a component of an entire sewer system. Rising mains are another, and are often separately assessed. However, these two components are integrated hydraulically and should be optimised in combination, not separately (Atkinson et al., 2000). To address a particular design problem an engineer could provide either a larger pump or relatively smaller diameter rising main, which would require more power than the alternative of providing a smaller pump and larger diameter rising main. These components thus require special attention in providing an optimal design.

Optimisation from a total systems point of view results in a higher level of efficiency. It includes taking pumping efficiency, pump choice and the equipment reliability into consideration. If this is not done the system can have high energy losses and therefore be uneconomic. Global energy supply and environmental conservation are high on the priority list nowadays (Ferman, 2008) and could also be evaluated by estimating the carbon cost. This is considered to be beyond the scope of this project.

4.3 Practical aspects pertaining to pump selection

In addition hydraulic theory, there are certain practical aspects that govern the selection of pumps and pipes. The internal clearance of a sewer pump, for example, must be large enough to handle solids of a prescribed size – in exchange for reduced hydraulic efficiency. An increased clearance between the impeller and the volute causes the pump to be less efficient. With a sewer pump the clearance size is a trade-off between pump performance and reliable operation. A multi vane or closed impeller pump would in theory be much more energy efficient than a vortex or open impeller type pump, but would block and clog more frequently, particularly if many unwanted items are expected in the sewage stream.

4.4 Planning and Decision-making

4.4.1 Decision support

Making technical decisions is part and parcel of engineering planning and design. Ang and Tang (1990) argue that the primary responsibility of engineers is to make decisions where risk is invariably incurred. Ideally, the decision making process is one that considers both technical and non-technical aspects to arrive at what could be considered the “best” solution for the given situation..

Decision support justifies a brief review given the fact that one of the two alternative software tools developed during this research was initially aimed at providing decision support relating to pump problems (this was not included in the SewPump tool, but future development of the work could move in this direction). Decision theory is concerned with identifying the known and unknown quantities and other issues relevant to a given decision, its rationality, and the resulting optimal outcome. Wikipedia (2010) defines a decision support system (DSS) as “a computer-based information system that supports business or organizational decision-making activities. These systems serve the management, operations, and planning levels of an organization.”

Different authors propose different classifications of DSSs and it is not the intention of this document to venture into the classification of these. DSSs also include knowledge-based systems. A properly designed DSS is described as an interactive software-based system that is intended to help decision makers compile useful information to identify and solve problems and make decisions. The information involved could be a combination of raw data, documents, personal knowledge, or business models (Wikipedia, 2010).

The most obvious advantages of a DSS are improved personal efficiency and that it speeds up the process of decision making. It also encourages exploration and discovery on the part of the decision maker, speeds up problem solving, generates new evidence in support of a decision and creates a competitive advantage over competition. A DSS also reveals new approaches to thinking about a problem space. In terms of intended improved design of sewage pump stations these benefits would of course be very useful.

4.4.2 Building blocks of decision support systems

Sprague (1980) provides an overview of the building blocks of any DSS, addressing specific issues regarding their functions, the different aspects to be considered and the expectations from different participants. He defines a DSS as a ‘class of information system’ that, with the aid of existing data, ‘interacts with other parts of the overall information system to support the decision making activities of managers and other knowledge workers in the organisation.’ He highlights the fact that people from different backgrounds will interpret the use of DSSs quite differently. Du Plessis (2010) stresses the importance for the development of a DSS with a specific target group in mind, so as to ensure that there are no uncertainties regarding the presentation of the results.

Sprague (1980) furthermore identifies a number of characteristics that need to be included in a DSS. These include factors such as flexibility, adaptability, decision focusing, user initiation and simplicity. Three levels are identified in DSS development:

- Specific DSS: This is referred to as an information system application, which might be hardware or software that allows a specific decision-maker to deal with specific problems.

- DSS generator: The DSS generator provides a set of capabilities to quickly and easily build a Specific DSS, as defined above. These capabilities include aspects such as reporting, graphics displays and statistical analysis subroutines.

- DSS tools: DSS tools are referred to as computer program languages such as Fortran/Visual Basic or Matlab. These programs are used to develop the DSS generator or Specific DSS.

During these different stages of development, the DSS must be able to respond quickly to user feedback, and must accommodate changes. It is suggested by Sprague (1980) that a DSS should be developed interactively with the users, and that it needs to allow for changes as it is developed, until it is relatively stable. He warns that a DSS will in all likelihood never be completely stable, but that the frequency of changes might be reduced significantly over time.

4.4.3 Decision support applied to sanitation in South Africa

Howard et al. (2001) developed a sanitation planning and reporting aid for the selection of appropriate sanitation technologies in developing communities. The aid is no more than a type of DSS. The authors of that work note that, with the provision of sanitation facilities, there is a risk of repeating the mistakes of the past and providing inappropriate facilities by not considering all the relevant variables. The outcome of the work by Howard et al. (2001) was a comprehensive planning aid that integrates all the relevant variables and at the same time provides for transparency and accountability in decision making. Such a tool was needed at the time and developed to enable the pragmatic delivery of sanitation services to those without access to them. However, pumps were not included in the research project at the time due to the fact that their project was limited to the choice of four sanitation types (VIPs and waterborne systems). The prototype decision support system of Howard et al. (2001) consisted of six indices which were primarily technically oriented:

- Water availability index
- Operation and maintenance index
- Economic index
- Site suitability index
- Ground and surface water pollution index
- Future planning index.

Each of the above indices used by Howard et al. (2001) were derived from a set of questions with selectable options, or entry of numbers. Equations were then used to convert the responses to index values. These index values were used as the foundation of the DSS to rank the options.

4.4.4 WhichSan decision support system

The WhichSan Sanitation Decision Support System (Branfield and Still, 2009) was developed locally as part of a WRC funded project for the purpose of selecting an appropriate sanitation system. WhichSan was developed to assist planners and engineers to consider the relative merits and costs of different sanitation options for a given situation. WhichSan does not address pumps, pump stations, or pump problems per se, but it is the most appropriate local decision support tool in terms of sewer systems. The reader of this text may find a review of WhichSan interesting and relevant.

WhichSan was presented as an MS Excel based tool with a matrix structure and the application of Visual Basic macros. An added aspect of WhichSan was the provision of Factsheets to provide additional information on some topics as independent and concise notes. The factsheets are similar to those presented by eWISA (www.eWISA.co.za) on various water-related topics. Similar FactSheets, termed InfoSheets, were subsequently developed as part of this project for inclusion in the SewPump tool.

4.4.5 Models for decision support

Models for decision support in water planning are more common and justify a brief review due to the close interaction between water and sewer services in most local authorities. Ang and Tang (1990) provide a detailed and comprehensive review of probability-based decision analysis and decision support models. However, their work does not focus on water and sanitation services.

Du Plessis (2010) provides a review of decision support models as they relate to water planning and develops a novel method whereby checklists and index values are used to aid management decisions pertaining to water demand management programmes. The objective of this model was to provide a user-friendly checklist for application by the manager of the department responsible for water and sanitation in the municipality to ensure that all factors in the water management cycle are evaluated during the process of decision-making, so as to ensure effective and efficient water use.

Froukh (2001) developed a decision support model for domestic water demand forecast, including WDM (not given in list of abbreviations) as a management option in the model. The DSS model developed by Froukh (2001) is, as with many other models, a computer-based model that needs a significant amount of input. Although the work touches on some of the criteria that do have the potential to reduce domestic demand, it still remains the responsibility of the user to define what criteria need to be included for evaluation.

Most of the South African municipalities investigated by Du Plessis (2010) indicated that they depend on support from outside to assist with the compilation of Water Services Development Plans (WSDPs), one of the most fundamental management tools in the water sector, as there were no internal resources to use DSSs, and particularly a multiple-criteria decision method (MCDM). This research ultimately steered away from a comprehensive DSS as output in line with the needs of the local service providers' staff, as any tool that would look even slightly complex would not be accepted and applied locally.

4.4.6 Multiple criteria decision making methods

Most decisions, and particularly those involving pumps, involve more than one criterion, thus implying that MCDMs would be needed. MCDMs have been proposed and reported on and include methods such as goal programming, additive value functions, multiplicative utility functions, and techniques for choosing weights such as direct rating, indifference trade-off and the analytical hierarchy process (Hobbs et al., 1992). The purpose of these methods is to provide information on trade-offs between different objectives and thus to help users make judgments in a systematic, coherent, and documentable manner. However, the wide variety of available techniques often overwhelms potential users so that in the end the decision is made without the aid of a DSS, or an inappropriate matching of methods with problems results.

Du Plessis (2010) cites more work where MCDM techniques have been recently reported in the literature and applied to water services. Techniques evaluated in published work include the following methods:

- Value function method: Assessing the performance of alternatives against set criteria, taking the relative importance of each criterion into consideration.

- Goal and preference point methods: Goals are specified, against which specific actions are measured.

- Outranking methods: Pairs of actions are compared against each other in a process of eliminating alternatives, based on all available information.

These methods differ from each other in the way criteria are considered: the application and computation of weights; the level of uncertainty; and the participation of different stakeholders. Hobbs et al. (1992) conducted experiments in which water planners applied more than one multi-criteria procedure to analyse problems by testing method appropriateness, ease of use, and validity. Among the conclusions reached were that experienced planners generally prefer simpler, more transparent methods, with additive value functions being the most popular. Strong evidence was reported that rating, the most commonly applied weight selection method, is likely to lead to weights that fail to represent the trade-offs that users are willing to make among criteria. Their final conclusion is that decisions can be as sensitive to the method used as the person who applies the method wishes make it. Applying that knowledge locally would mean that a robust and simple system (possibly not including DSS per se) may perform better than a highly specialised technique.

One option aimed at keeping the output of this project uncomplicated would be to use software that is commonly accepted in technical circles, such as MS Excel or HTML, in developing the output. Levine et al. (1998) go to great lengths to advocate Excel as a powerful decision making tool. They describe the use of Excel to create payoff tables, opportunity loss tables, and decision trees, show how to select the criteria that may be used to select the most desirable course of action, and finally describe the return to risk ratio and the concept of utility curves. MS Excel was used for developing one of the two alternative tools as part of this research, but in the end an HTML-based product was preferred.

4.5 Planning for future flow rates

There are a number of ways to control the flow to a pump in order to meet a required flow rate and more importantly, to meet an estimated future flow rate. The most basic approach would be to use a throttle valve to regulate the flow, but such an application would cause unnecessary energy losses in a system that in turn would increase the energy cost – and the risk of blockages would increase.

Reduction in impeller size would be a better way to deal with an oversize pump as there is not as much energy lost as there is with a throttle valve. This can give the designer the option to upgrade to a bigger impeller if the demand should increase, eliminating the need to replace the entire pump at a much higher cost and saving money in the process. The cost implication of selecting a pump configuration to cater for future flow demands should be calculated and compared with the saving of costs related to an efficient pump configuration that meets the actual flow demand for a shorter period. It could well be that the savings in electricity costs for the efficient pump could pay for the pump upgrade to meet an increased future flow demand.

4.6 Risk-based prioritisation for pump decommissioning

Most service providers would like to see their sewer systems rid of all pumps. In some cases this is practical, while in others not. A recent study by GLS Consulting provides a method for evaluating the decommissioning of (existing) sewer pump stations with the aim of replacing the pumps with deeper gravity sewers. A brief summary of the process is presented in this section and could form the basis for similar work elsewhere. The idea of assessing whether a pump station is needed (versus its possible replacement) could be incorporated into the decision support tool if deemed appropriate, but at this stage the tool does not include this aspect.

In the work by GLS the current pumping capacity for each pump station in a system was compared to the maximum inflow into a specific pump station (as per hydraulic models). The pump stations experiencing overflow problems were identified by the service provider's operational staff. A combined list of problematic/overflowing pump stations was subsequently derived. For each of the pump stations in the combined list a value (between 0 and 1) was given based on the maximum inflow into the pump station relative to the maximum inflow of the most critical pump station.

A detailed physical condition assessment was done for each pump station as part of the requirements of the asset register. According to the condition assessment every pump within a specific pump station was given a grading of “Very poor”, “poor” or “Fair”. GLS used these condition grades to derive a condition scoring system whereby points were awarded. Because the number of pumps within the pump station varies and because the condition of all pumps within the same pump station varies, a weighted score for each pump station had to be calculated. For each of the pump stations a relative value (between 0 and 1) was given based on the weighted condition score of the pump station relative to the weighted condition score of the most critical pump station.

The maximum inflow into the specific pump station (as per hydraulic models) was used to calculate the proportion of annual running energy costs, maintenance costs (sump cleaning etc.) and capital cost (replacement of pumps etc.). Taking the total annual operational costs of the pump station and the total project cost to phase out the pump station into consideration, a cost-benefit timeframe could be calculated for each pump station that is the time in which the saving on annual operational costs can pay off the initial capital spent on phasing out the pump station.

For each of the pump stations a relative value (between 0 and 1) was given based on the costs-benefit timeframe of the pump station relative to the cost-benefit timeframe of the most critical pump station. This led to what was termed a priority index calculation.

The relative values for each of the scoring categories as described above was combined with a weight factor for each of the categories to derive a priority index value for each pump station in the system. The priority index value for each pump station was then calculated. The priority index value for each pump station was ranked and the list of pump stations was ranked according to their priority index value. The results for the top 20 most critical pump stations to be phased out were provided for discussion with the service provider for budgeting and planning purposes. Feasibility investigations for each of the proposed phasing out projects could then be done, before commencing with the phasing out of the selected pump stations.

In developing the output of this research project and software tool, the input required for the abovementioned risk-based approach was evaluated. It was considered essential to include a method whereby an operator could construct a log of problems for each pump station under his jurisdiction and communicate this to higher level staff members.

4.7 The 4 A's and European Framework

In moving towards problem classification and a framework for sewer pump problems, a planning framework for flood risk and water management at city or county scale reported on by Blanksby et al. (2011) provided useful background. The work presented integration of various European approaches to what could be seen as "problem" events. In referring the work by Blanksby et al. (2011) and others the reader is reminded that many European countries are faced with problems of combined sanitary and storm sewers – that is dissimilar from the separate sewers in South

Africa. Nonetheless, the approach to unwanted problem events in Europe provided a useful reference in developing a framework handling problems with for sewer pump in South Africa.

Blanksby (2011) reports on a European framework which recognises the need to draw together the different aspects of flood risk management, namely the Scottish Government's Four A's approach (FIAC, 2007), the partners in the EU Interreg projects FloodResilienCity (FRC), Managing Adaptive Responses to Changing Flood Risk (MARE) and Skills Integration and New Technologies (SKINT). Their framework, whilst retaining the processes of prevention, protection, preparedness, emergency response and recovery the lessons learned provide a visualisation in which activities may be carried out in a parallel processes. This is illustrated in Figure 4-1, adopted directly from Blanksby et al. (2011), where the concept is further extended to a framework for sustainable land, city and water management as depicted in Figure 4-2. The helical arrows in Figure 4-1 represent the interactions between the As. The well-known 4 A's now become 6, grouped as:

- Awareness of flood risk management
- Analysis and assessment of flood risk
- Alleviation and avoidance of flooding and
- Assistance prior to, during and after flood events.

In personal discussions with Blanksby et al. (2011) a large number of decision support tools were discussed, mainly based on a "Who does what and why analysis", and its related benefits. Who does what analysis is a simple tool which helps to construct a picture of what the stakeholders in any process do. The analysis is performed by simply completing a series of four check lists, describing partner involvement in flood alleviation and avoidance. It could be viewed as a method to link responsibilities to tasks, and is thus somewhat different to the aim of this research, where specific pump station components are linked to potential problems and possible solutions. The concept of providing simple printed checklists (that a user can tick with a pen on paper, or on MS Excel based sheets) was found to work well in the European environment.

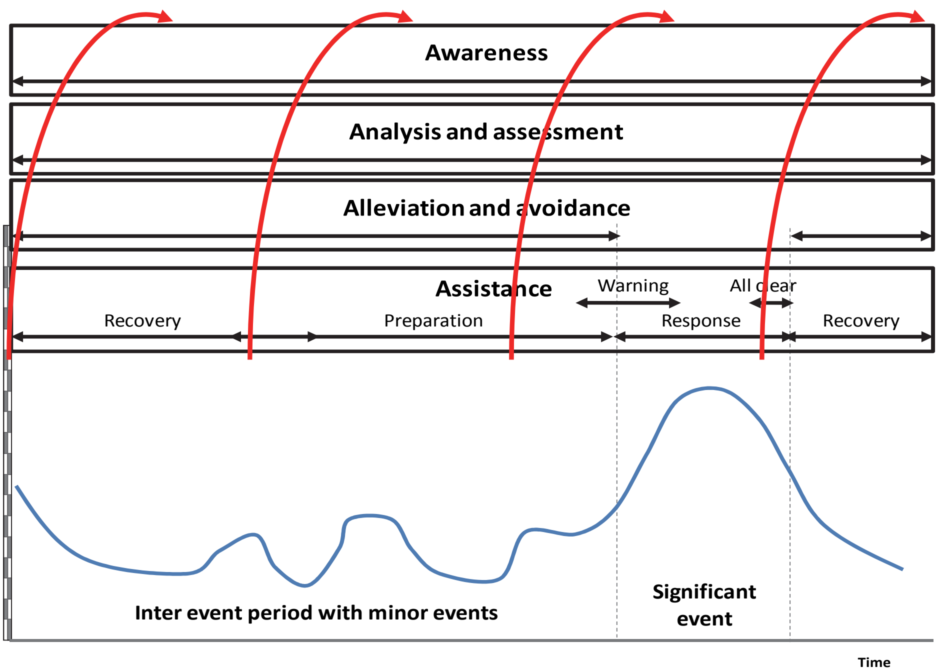


Figure 4-1. The flood risk management framework (Blanksby et al., 2011)

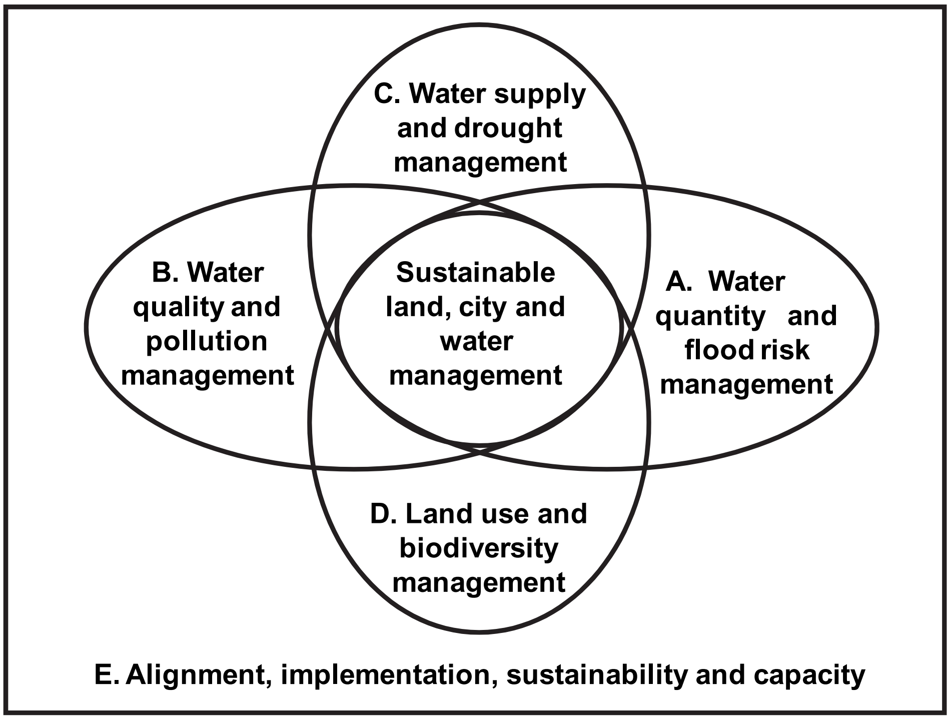


Figure 4-2. Framework for sustainable land, city and water management (Blanksby et al., 2011)

5. PUMP STATION PROBLEMS AND CLASSIFICATION

5.1 Overview of Pump Station Problems

5.1.1 Quantifying problems

Identifying, listing and classifying the problems and how the measurement of the intensity or extent would be quantified was a particular challenge faced by the research team. One possible method would be by means of assessing the system reliability. The outcome from this would not be generically applicable and is not as amenable to future optimisation as other methods. The term “problem” is used loosely in this research project, despite the understanding that in a pure technical sense the definition could be linked to system reliability. However it was not possible to quantify problems in this sense suggesting that an alternative approach be used allowing for less precise values to be described and evaluated, such as logic set theory and fuzzy logic.

A clear distinction needs to be drawn between problems and their causes. If the underlying causes are not identified and addressed, the problems will keep recurring. A broken pipe joint just upstream of the pump station could cause an excessive amount of silt being washed into the sewer and being deposited in the sump, requiring frequent clearing. By repairing the joint the cause is addressed and the problem no longer occurs. There will be situations where addressing the underlying cause is beyond the scope of the study, but this does not mean that the cause should not be identified, or should be ignored. When this happens it will be necessary to develop a needs of coping with the problem.

5.1.2 Direct versus indirect problems

This section could be considered as one addressing problems (direct) versus the underlying causes (indirect). The effort at addressing the problem at a sewer pump could be distracted from its focus by tracing the problem back to the underlying cause. These underlying causes may have to be considered as the actual issue to be addressed. However, the emphasis here is to address particular problems relating to pump stations in the most direct way possible at the pump stations. During the problem identification phase of the project it became apparent that boundaries had to be established to prevent the proliferation of problems and their causes that were beyond the scope of the study. A problem was therefore limited to an issue that could be determined by means of inspection at the pump station site, discussion with the operation and maintenance staff, or by reviewing documentation covering problems.

The issues are thus not only indirect problems, but underlying causes. This is best illustrated by means of an example: Consider a clogging problem caused by unwanted solid objects fed into the sewage stream at residential toilets. This is probably the most likely cause of various unwanted solid objects in the waste stream and subsequent problems (refer also to Table 4-1). This problem is caused as the toilet users are poorly trained or untrained in the use of a toilet (the underlying cause is poor or no consumer education). Addressing these underlying causes would add an additional and unwanted level of complexity to the framework and subsequent tools that are being developed as part of this project, and were included simply as notes where appropriate. They nevertheless need to be identified.

5.1.3 Methodology for identifying problems

Pumping sewage poses various problems. One of the most problematic noted during this research is overflows. A comprehensive list of common problems was compiled from literature, site visits and stakeholder interviews during this research. The listing by Van der Merwe-Botha and Manus (2011) and Sidwick (1984) of some common problems relating to sewers and pumps is the only local peer reviewed report of this nature that could be found during the knowledge review.

In this study problems at sewage pump stations were identified following an in depth literature study in conjunction with a combination of field visits and stakeholders interviews at selected sites in the Western Cape, Gauteng and KwaZulu-Natal. The causes of sewage pump station problems were investigated where possible, as described earlier in this report, in order to better understand the development of a framework for classifying the problems.

5.2 The Most Significant Problems

5.2.1 Clogging by unwanted solid objects

Unwanted objects are also referred to as "foreign objects". The term broadly describes all types of waste matter (litter) and visible, insoluble particles. The accumulation of solids can lead to blockages or damage to pump impellers (Ashley et al., 2004). Some solids find their way into the sewers through households and other through manholes. Entire text books have been devoted to the topic of solids in sewers (Ashley et al., ibid.). The problem is common in both storm sewers and foul sewers. Sewer systems can of course incorporate certain design details and features to control these problems (Ackers et al., 1996).

The ineffectual removal of grit from sewers can cause it to accumulate downstream in pipes or sumps with inefficient pump operation as result (van der Merwe-Botha and Manus, 2011). Sand is a major problem in Western Cape sewers as it accumulates in sumps, which then have to be cleaned regularly. The grit shortens the life of pumps due to added abrasion.

The presence of unwanted objects per se does not constitute a problem, but the resultant clogging does. The clogging problem would never have occurred if it were not for the unwanted objects. The objects are easily identifiable by inspection and for this reason were considered direct causes in their own right.

5.2.2 FOG products

A major cause of blockages in sewers could be ascribed to hardened insoluble FOG deposits. Of all the sewer overflows reported annually in the United States, about 48% are due to sewer line blockages, of which 47% are related to FOG deposits that constrict the flow in pipes (He et al., 2011). These FOG deposits also build up around pump sump level probes and the probes then get stuck or malfunction, resulting in pump burnout or sump overflows. As is the case for unwanted objects, FOG deposits were considered a direct cause in their own right.

5.2.3 Peak flows

Wet weather peak flows during rainfall events could result in overflows at pump stations. Another cause of excessive peak flows is holiday periods. During these periods some areas report vast increase in the sewage flow rate. Hermanus, in the Overstrand Municipal region, is an example. Thousands of people visit the relatively small town during vacations and sewer flows increase dramatically.

5.2.4 Design problems

Various problems could be traced back to the design of the pump station. There is often a divide between theoretical designs of pump stations by engineers and the practical operation and maintenance of pump stations by local authorities. Improper construction of pump stations can lead to structural failures, or inefficient operation.

Pump sump geometry has to be optimized to mitigate against stagnant conditions. This enhances the moving of solids in the sump so that pumping is more efficient (Czarnota, 2008; Reade and Crow, 1994). Jones (2008) presents a summary table of the type of problems that could be expected at pumps. The mechanical failure of pumps can be caused by various factors, one being the incorrect pump selection for a particular application. This can lead to cavitation, under-performance, over-pumping (burning out), impeller failure, or seal failure.

Pump station layout should encourage regular and efficient maintenance.

5.2.5 Maintenance and operation

Good maintenance requires that SHD's need to be cleaned on a regular basis to prevent blockages. Mechanically raked screens also need to be checked regularly, because their teeth are vulnerable to breakage and bending (Nozaic and Freese, 2009). The maintenance of sewage pump stations is a daily struggle for some local authorities, as was noted during site-visits and previous reports. Van der Merwe-Botha & Manus (2011) identified various potential hazards with maintenance work.

5.2.6 Electrical power supply

Power outages result in pumps and telemetry systems not being able to operate, unless of course back-up power is provided. When pumps cannot operate due to power failure, generators should be available to power the pumps. However, if a generator is not available the station will overflow of if power is not restored before the emergency sump fills.

5.2.7 Other problems

Some other possible causes of problems include odours, health and safety of maintenance staff, theft, vandalism and unauthorized access. Odours were noted as one of the first problems reported by consumers and constitute a problem in their own right during normal pump station operation they create unsafe working conditions and in combination with oxygen lead to the serious corrosion of many materials.

5.3 Categorising Problems

5.3.1 The concept of categorisation

A detailed account of categorisation is beyond the scope of this project, but a brief review is considered necessary in order to clearly present the subsequent framework and fuzzy-based illustration. Cohen and Lefebvre (2005) described categorisation as the process in which ideas and objects are recognised, differentiated and understood. This same definition is adopted by the internet encyclopaedia Wikipedia (2012). The OED (2010) defines the word categorise as follows, "to put people or things into groups according to what type they are".

Categorisation thus entails the grouping, or sorting of certain objects into pre-defined categories for some specific purpose, based on logical relationships between these objects. Ideally, a category would illuminate the relationship between the subjects and objects of knowledge. Categorization is fundamental in many fields of study, including decision making.

According to the classical view (also called the Aristotelian view) of categorisation, each category must be comprehensively defined, mutually exclusive and collectively exhaustive. This means that any object, or pump problem, in the entire data set to be classified would belong unequivocally to at least one, and only to one, of the categories. This stringent approach is not always applicable to complex systems and more advanced methods have been devised with time. Conceptual clustering is a modern variation of the classical approach, and derives from attempts to explain how knowledge is presented conceptually. This would involve classes, to which entities belong based on conceptual clustering, versus categories to which objects would belong as per the classical view.

One of the major flaws made with categorisation is when objects are placed in a category where they do not belong. This is termed miscategorisation. In order to prevent miscategorisation, a logical basis is needed for classifying the objects. Miscategorisation occurs when dissimilar objects are accidentally grouped together based upon common denominators (any object would have this variable in common), or illogical denominators. Another common way in which miscategorisation occurs is through over-categorisation of objects with subsequent miscategorisation based on over-similar variables that virtually all things have in common. The major advantage of conceptual clustering over the classical technique is that it notably reduces the chances for miscategorisation.

Consider for example the simple case of a power failure, leading to an overflow and subsequent odour problem. What is the problem and how would it be classified? Apart from the actual electricity failure this particular "problem" could correctly be described as any one of the following: insufficient emergency storage and thus insufficient pump sump size, the lack of backup power, odour problems (due to the spillage), or even some other matter like stormwater ingress or excess peak inflow during a rain event combined with any of the former. It is clear that miscategorisation is imminent if the classical approach were considered.

As part of this research conceptual clustering was thus used to place the different entities (the sewer pump problems) into various classes by first formulating the conceptual description of each class and then classifying the entities according to the descriptions of each class. Conceptual clustering is related to fuzzy set theory, in which objects may belong to one or more groups (in this case the classes), in varying degrees of fitness. This makes sense for the classification of sewer pump problems, where a given pump station problem could belong to more than one of the classes, but in varying degrees of membership in each case.

5.3.2 Existing risk categories

The City of Cape Town has listed five main risk categories associated with sewer pump stations. The five categories identified by (Samson, 2011) are:

- Mechanical failure of duty pump sets
- Mechanical failure of duty and standby pump sets
- Electrical failure within the pump station
- Power outages
- Blockages of the SHD.

These categories are an example of what could be found during the knowledge review, but none covered the wide range of pump problems identified during this project. Maintenance management systems were found to present lists of problems, and in some instances there was some form of categorisation. However, by the nature of the work the systems focused on mechanical and electrical problems only, or often only on pump problems in contrast to pump station problems (which may include for example vandalism and theft, or site access problems).

For this reason a broader framework encompassing a wider range of pump station problems was developed during this research project.

5.4 Framework for Sewer Pump Station Problems

5.4.1 Conceptual basis for framework and problem classes

The approach followed in this research was that the problem classes for the framework could be derived by starting in a simple way and successively adding complexity based on subjective judgement and stakeholder input. Knowledge from technical staff responsible for sewers was continually gained and fed into the process, thus building towards a relatively robust framework that would incorporate all types of problems reported by stakeholders and noted during site visits respectively. The research team based the methodology of this study on successful frameworks derived elsewhere. The comprehensive and elaborate European Union (EU) framework for flood disaster management is an example of a robust framework allowing for stakeholder participation, as well as roles and responsibilities, so it is more extensive than the framework presented in this research. Ashley et al. (2011) report that the EU framework, whilst retaining the processes of prevention, protection, preparedness, emergency response and recovery and lessons learned, provides a visualisation in which activities may be carried out in parallel processes, which may intertwine and merge or separate as appropriate. The EU framework links specific roles and responsibilities to each component of the framework. The Scottish Government’s Four A’s approach (Ashley et al., 2011) was incorporated into the EU framework reported on by the same authors, but was extended to 6 A's and grouped as follows:

- Awareness – of flood risk management;
- Analysis – and assessment of flood risk;
- Alleviation – and avoidance of flooding; and
- Assistance – prior to, during and after flood events.

Sewer pump problems were considered amenable to the same approach in that the A's listed above would provide the basis for a framework to address and resolve problems. The sewer pump station problem framework would thus incorporate tacit knowledge as well as experience to make logical sense from the quagmire of information. When considering sewer pump station problems, the idea at the outset of this research project was thus to limit the framework to no more than 6 classes (or pillars), but ideally to have only 4 classes.

5.4.2 The four O’s

Sewer pump station problems were ultimately categorized into four classes. Each direct problem identified in the first phase of the project could ultimately be placed into one (or more) of these four problem classes, based on a degree of membership to each class. In presenting the framework here, aspects regarding roles and responsibilities were not included, so as to maintain the focus. These would be an obvious future extension to the framework presented here. The four classes ultimately arrived at were coined the four O’s of sewage pump station problems, namely:

- Overflows
- Odours
- Operational (and maintenance)
- Other.

These four classes are discussed in more detail along with explanatory tree diagrams in the following section of the text.

5.4.3 Overflows

Overflows were noted to be one of the most common and undesirable sewage pump station problems during stakeholder engagement. Overflows occur when the total sewerage volume arriving at the pump station exceeds the available storage in the sump. Sewage thus spills over the top of the pump structure and makes its way overland to the nearest drain point or watercourse. Various problems relate to overflows. The framework for Overflows is illustrated by the diagram in Figure 5-1.

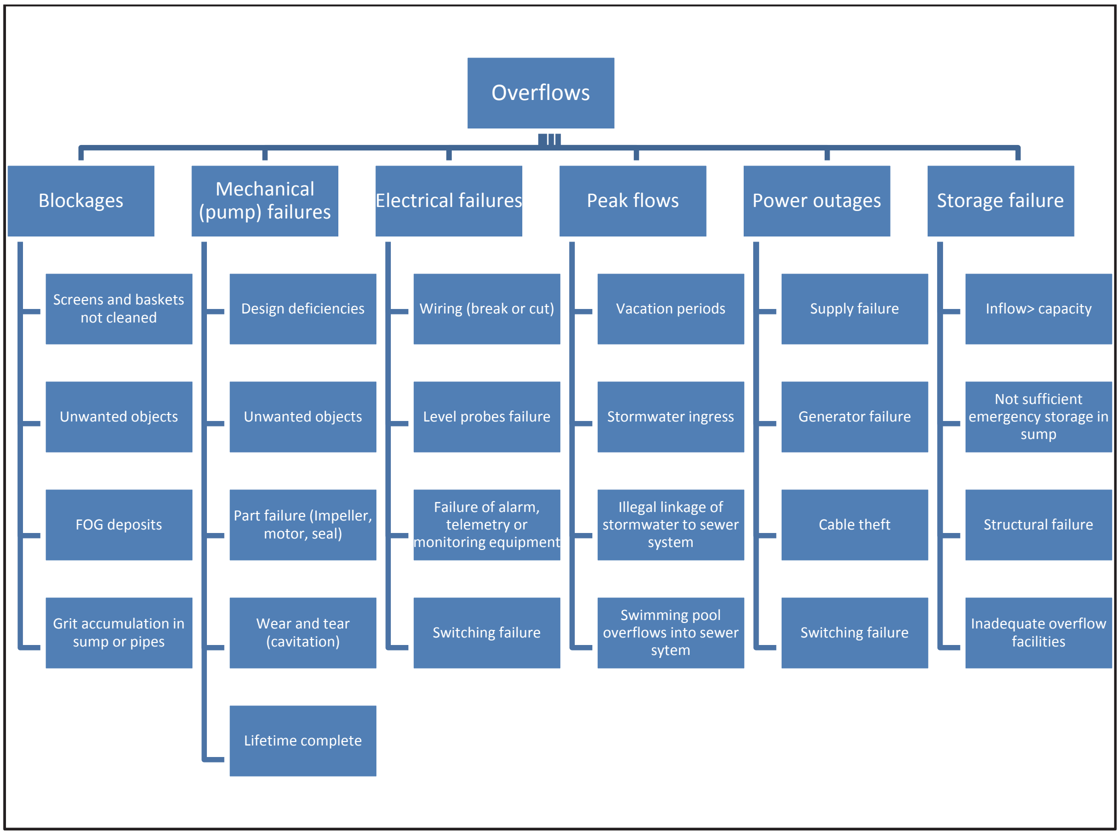


Figure 5-1. Framework for Overflows

5.4.4 Odours

Odour problems are very common due to the nasty smell of raw sewage. They can be present and pose a problem even under normal working conditions. Odour problems are worse during overflows. The framework for odours is presented in Figure 5-2.

This schematic presented in Figure 5-2 could be extended to include a further branch called "Upstream conditions": if upstream gradients were very flat insufficient oxygen would be entrained in the effluent, it would go septic and H_2S is generated. When the H_2S is stripped out it leads to a terrible stench, known as "the rotten egg smell", which is different from the smell of normal sewage. This could escape at the downstream exit, at the pump station sump. However, as part of this study, problems pertaining directly to the upstream gravity system were considered beyond the scope of this investigation.

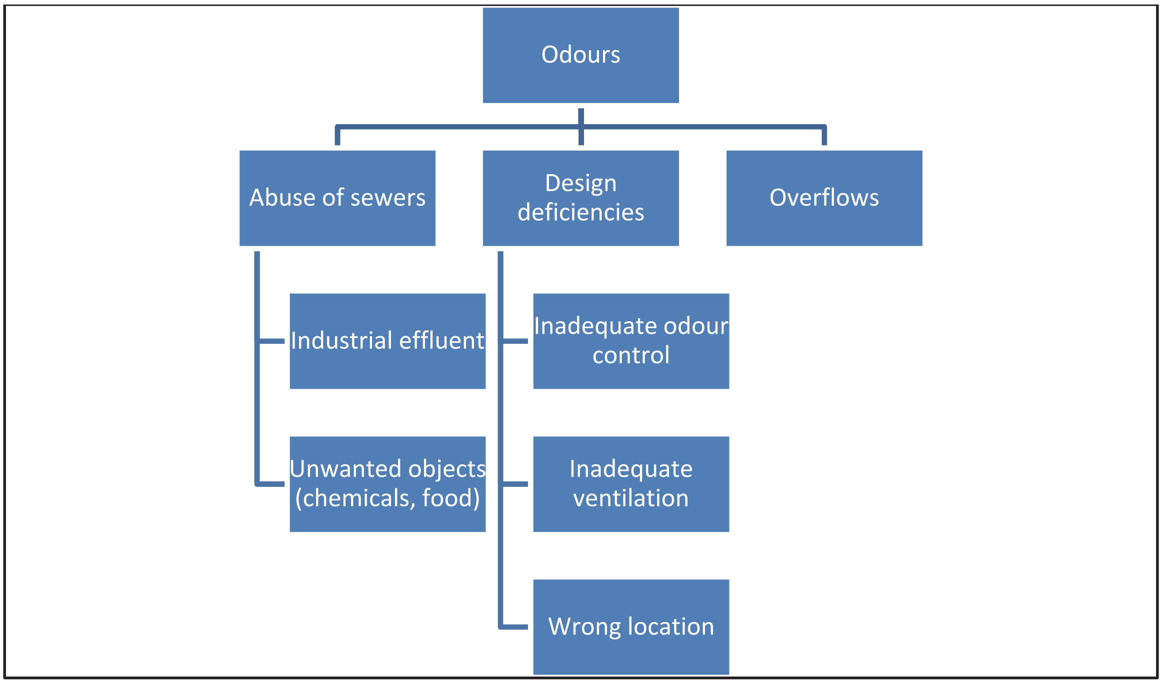


Figure 5-2. Framework for Odours

5.4.5 Operational problems

Operational problems relate to all aspects of operations and maintenance. The pump station may still operate although operational problems persist. Shiels (2001) provided an initial basis for the operation and maintenance framework by listing the following typical maintenance problems:

- Insufficient suction pressure to avoid cavitation (level probes should be working at sufficient height)
- Excessively high flow rate to maintain the net positive suction head of the pump
- Prolonged operation at lower than acceptable flow rates
- Operation of the pump at zero or near zero flow rates
- Improper operation of pumps in parallel
- Failure to maintain adequate lubrication for the bearings
- Failure to maintain satisfactory flushing of mechanical seals.

Unfortunately these all relate to the pump per se and it is apparent that some other aspects need to be added to present the larger picture at pump stations. The framework for operation and maintenance problems is presented in Figure 5-3.

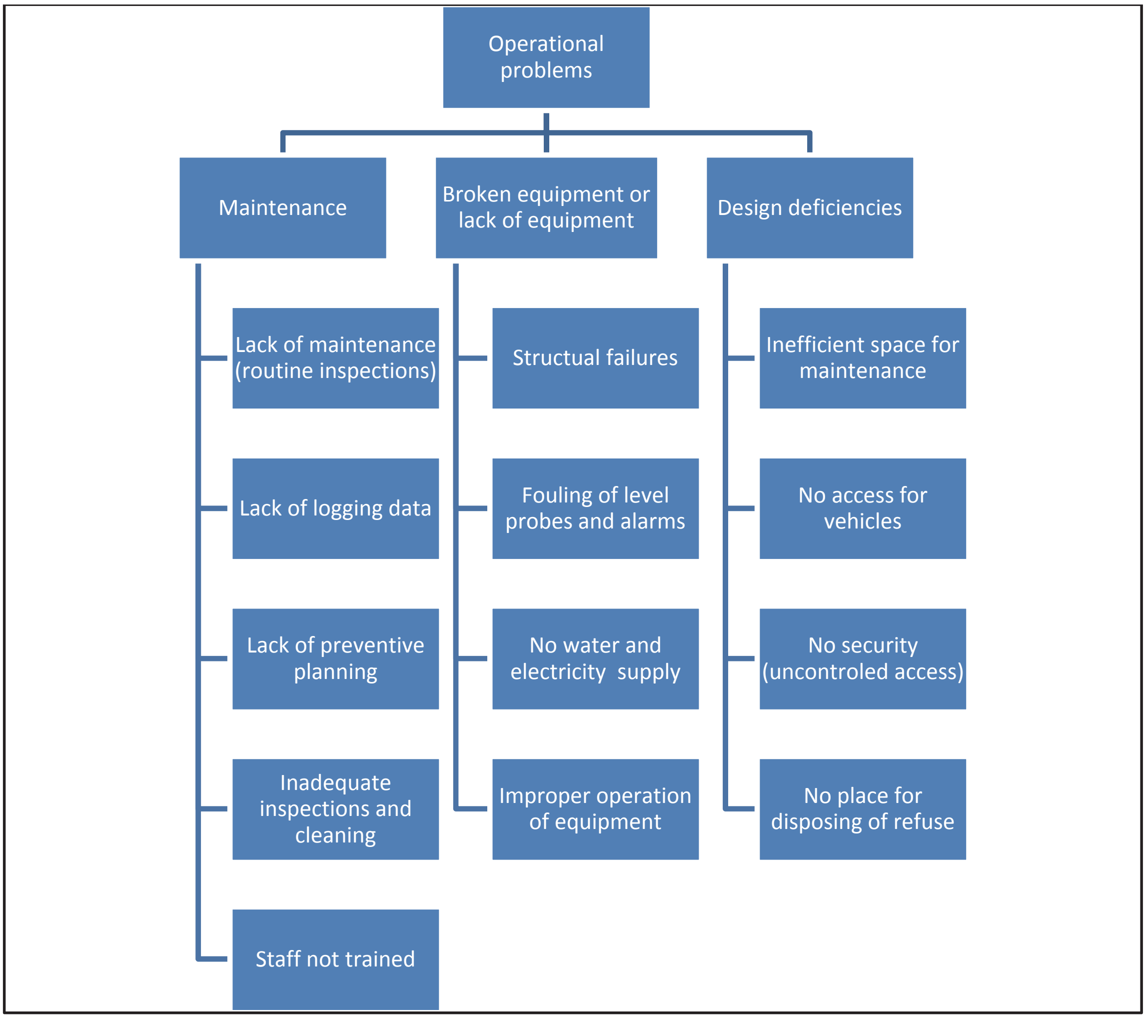


Figure 5-3. Framework for Operation and maintenance

5.4.6 Other problems

Other problems refer to miscellaneous problems not suitably placed in any of the above classes. The most notable of these pertains to criminal activities, as well as health and safety issues. Criminal activities are present throughout South Africa – and the world for that matter – and were often reported during the site visits and stakeholder interviews. Municipal staff in various towns of the Western Cape reported theft to be a serious problem during site visits and fencing around the pump stations was seen as a first line of defence. Some pump stations were equipped with security alarm systems to deter vandalism and theft. The framework for other problems is presented in Figure 5-4.

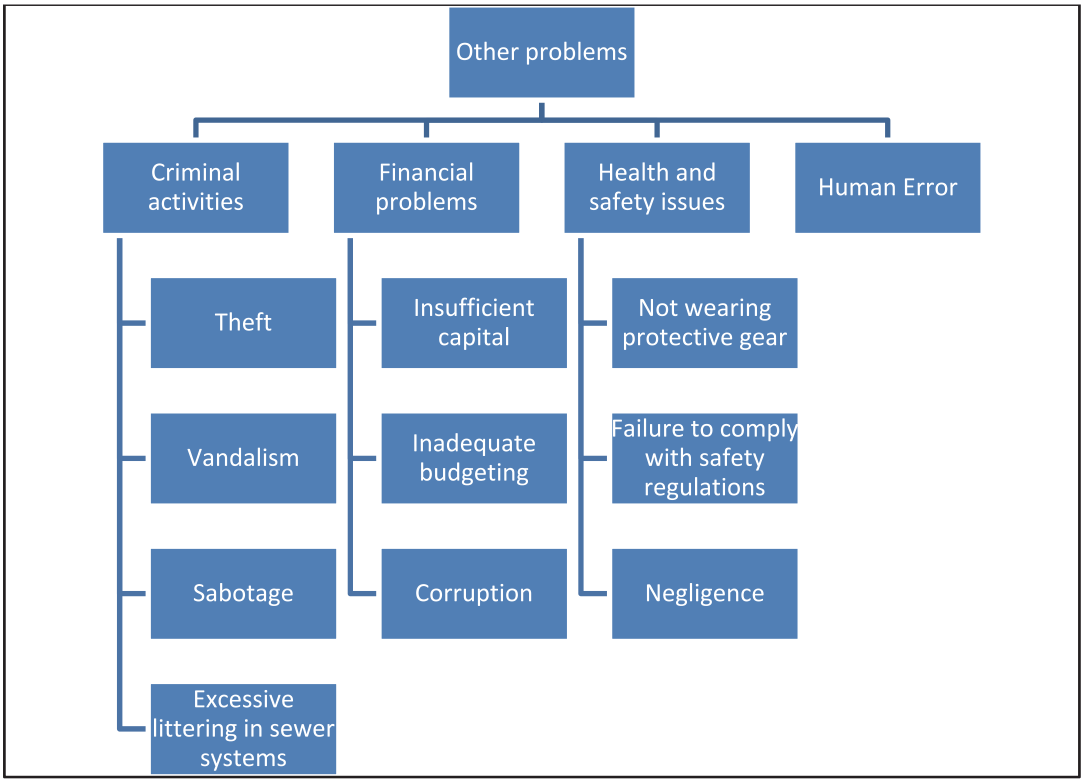


Figure 5-4. Framework for Other problems

5.5 A fuzzy-based decision support tool for sewer pump problems

5.5.1 Fuzzy set theory

This section provides a brief overview of fuzzy set theory and illustrates the possible future application to the framework of the four O's in further developing a decision support tool pertaining to sewer pump station problems. Fuzzy set theory comprises three components, namely fuzzy sets representing system inputs, the rule space that is typically presented as a set of IF-THEN statements and the system outputs. A fuzzy system uses rules to match any set of input-output data and is useful in developing decision support systems.

Ostojin et al. (2011) applied fuzzy logic to optimise energy costs at a sewage pump station by modifying the on-off switching rules for pumps on combined sewers. Ostojin et al. (ibid.) further derived a genetic algorithm search technique to adjust the parameters that define the membership functions in the fuzzy rules, in order to provide automated minimization of the energy costs towards an optimal solution. From their work it is evident that a thorough foundation and solid framework could lead to the application of advanced techniques in terms of further decision support and optimisation. This paper uses a robust approach of subjectively weighed decision matrices for each sub-set, with subsequently derived ranked index values to illustrate the application.

5.5.2 Fuzzy sets

Fuzzy sets are described domains of the inputs, each of which is thought to have a definite effect on the output. The system input parameters are defined by the analyst. As an example, Ostojin et al. (2011) combined the rate of level change in the pump sump and the actual level in the sump as inputs. Any number of inputs could be used. In developing an automated control system for sewage pump stations in Taipei city Chiang et al. (2010) used input parameters for water level, precipitation, status of pumps, status of sluice gates and the predictive water level as a basis for their fuzzy sets.

In this case the inputs are the entire set of pump station problem entities, each classified and thus belonging in some degree of membership to conceptual classes – the four O's. Each of these classes is sub-divided into a number of sub-classes as discussed earlier, and thus comprises different inputs depending on the particular sub-set evaluated.

Turn again to the example presented earlier: the simple case of a power failure leading to an overflow and subsequent odour problem. It is now possible to identify as an output some type of rank to determine what problem would be the most "notable" in terms of the rule space. This would not tell the analyst how to solve the problem, but would aid in identifying the problem that is expected to be the "worst" as defined by the analyst setting up the rule space. The values of system inputs are defined by a degree of membership, with membership values given in integers ranging from 1 to 5 in this case. The framework of the 4 O's allows for robust yet flexible application of fuzzy set theory.

5.6 Illustration of possible fuzzy logic application

5.6.1 Conceptual application to the 4 O's

Most of the problems identified during this study occur in some complex inter-action with one another. For instance unwanted objects in the upstream flow stream would lead to problems like, blockages and pump damage. If a blockage occurs the result may be an overflow and an overflow might also result in odours. A degree of membership needs to be assigned to a particular problem entity. This allows for rating the significance of the problems as an output.

5.6.2 Illustrative application to the class for "Overflows"

The application of fuzzy logic is demonstrated as it pertains to the class for Overflows. Plugh's method comprises a basic decision matrix to compare a set of statements, or problem entities in this case, in terms of some criteria by allocating a weight to each based on subjective decisions (Ullman, 1992). Each entity is given a weight in this manner by comparing it to other entities in the same sub-set by allocating a score between 1 and 10. The criterion with "higher importance" based on the subjective series of decisions, thus receives the higher score and subsequent higher ranking. The problem entity with the highest weight receives the highest rank representing the degree of membership.

The class for Overflows comprises six sub-classes namely: blockages, mechanical failures, electrical failures, peak flows, power outages and storage failure. Each of these comprises a set of problem entities, or events causing blockages. These individual problem entities were scored against each other using Plugh's method, as demonstrated in Tables 5.1 to 5.6 for:

- Blockages
- Mechanical failures
- Electrical failures
- Peak flows
- Power outages
- Storage failure.

Table 5-1. Evaluating weights of Overflows – events causing blockages

	SHD not cleaned	Unwanted objects	FOG deposits	Grit accumulation
SHD not cleaned	*	7	6	5
Unwanted objects	3	*	4	4
FOG deposits	4	6	*	6
Grit accumulation	5	6	4	*
Weight	**12**	**19**	**14**	**15**

There are four causes (or entities), but 12 interactions (16-4). Another way of defining the relationship between the columns and rows would be to classify the causes as primary and secondary respectively. With this approach the influence of A on B is clearly differentiated from the influence of B on A.

Subjective scores are allocated to each entity in comparison to the rest. This would typically be done in collaboration with technical and maintenance staff. This decision procedure is site specific. Consider for example one where an automated SHD operates with few problems. It would have a very low score allocated to "SHD not cleaned", while at the other end of the scale a SHD where a manual cleaning process is used and the cleaning process is plagued by regular problems the score when compared would be very high. The scoring of weights in Table 5-1 to Table 5-6 is based on a relatively small pump station that was considered typical of those visited during this research project in the Western Cape. The rank was subsequently obtained from the weight in Table 5-1. The values listed below describe the degree of membership of each entity as an integer used in applying the fuzzy logic rules:

- Screens and baskets not cleaned = 1
- FOG deposits = 2
- Grit accumulation = 3
- Unwanted objects = 4.

The entity with the lowest weight would be the one that was considered to be the least significant in terms of its impact (compared to the others in this sub-set), and therefore would receive the lowest score. This technique was applied to all the other sub-classes. The evaluation of entity weights is presented in Table 5-1 to Table 5-6, with the subsequently derived rank for all the sub-classes (including the scores in the bullet list above), summarised in Table 5-7.

Table 5-2. Evaluating entity weights for mechanical failures

	Design deficiencies	Unwanted objects	Parts failure	Wear and tear	Lifetime complete
Design deficiencies	*	7	6	4	4
Unwanted objects	3	*	5	4	3
Parts failure	4	5	*	4	4
Wear and tear	6	6	6	*	6
Lifetime complete	6	7	6	4	*
Weight	**19**	**25**	**23**	**16**	**17**

Table 5-3. Evaluating entity weights for electrical failures

	Wiring	Level probes failure	Failure of alarm, telemetry or monitoring equipment	Switching failure
Wiring	*	4	3	4
Level probes failure	6	*	4	5
Failure of alarm, telemetry or monitoring equipment	7	6	*	7
Switching failure	6	5	3	*
Weight	**19**	**15**	**10**	**16**

Table 5-4. Evaluating entity weights for peak flows

	Vacation period	Stormwater ingress	Illegal linkage	Swimming pool overflows
Vacation period	*	6	5	3
Stormwater ingress	4	*	4	3
Illegal linkage	5	6	*	4
Swimming pool overflows	7	7	6	*
Weight	**16**	**19**	**15**	**10**

Table 5-5. Evaluating entity weights for power outages

	Supply failure	Generator failure	Cable theft	Switching failure
Supply failure	*	6	6	4
Generator failure	4	*	4	3
Cable theft	4	6	*	4
Switching failure	6	7	6	*
Weight	**14**	**19**	**16**	**11**

Table 5-6. Evaluating entity weights for storage failure

	Inflow> outflow	Insufficient emergency sump storage	Structural failure	Inadequate overflow facilities
Inflow>outflow	*	4	4	4
Insufficient emergency sump storage	6	*	4	4
Structural failure	6	6	*	6
Inadequate overflow facilities	6	6	4	*
Weight	**18**	**16**	**12**	**14**

Table 5-7. Degree of membership for entities per sub-class for Overflows

Blockages (5-1)	Mechanical failures (5-2)	Electrical failures (5-3)	Peak flows (5-4)	Power outages (5-5)	Storage failure (5-6)	Degree of membership
Screen and baskets not cleaned (12)	Wear and tear (16)	Failure of alarm, telemetry or monitoring equipment (10)	Swimming pool overflows (10)	Switching failure (11)	Structural failure (12)	1
FOG deposits	Lifetime complete	Level probes failure	Illegal linkage	Supply failure	Inadequate overflow facilities	2
Grit accumulation	Design deficiencies	Switching failure	Vacation period	Cable theft	In sufficient emergency sump storage	3
Unwanted objects	Parts failure	Wiring = 4	Stormwater ingress	Generator failure	Inflow > outflow	4
	Unwanted objects					5

The ranked value of each entity given as the weight at the bottom of each column in Tables 5-1 to 5-6 is listed in Table 5-7 providing a measure of the degree of membership. It would be possible, of course, to assess the weights in a different manner allowing for more complex decision methods, but the illustrative example presented is considered useful for the purpose of illustrating the possible future application of the problem framework presented in this text to any problematic pump station. The method was also extended to distinguish between the six sub-classes of Overflows. These sub-classes were subsequently weighed against each other in the same manner as before. The result is presented in Table 5-8, with a rank for each sub-class.

Table 5-8. Degree of membership ranked per sub-class for Overflows

	Blockages	Mechanical	Electrical	Peak flows	Power outages	Storage failure
Blockages	*	3	3	4	4	5
Mechanical	7	*	5	6	6	7
Electrical	7	5	*	6	5	5
Peak flows	6	4	4	*	4	6
Power outages	6	4	5	6	*	6
Storage failure	5	3	5	4	4	*
Overall Weight	**31**	**19**	**22**	**26**	**23**	**29**

The main causes of overflows can now be considered as fuzzy sets. Each fuzzy set has been allocated a representative value, with degrees of membership for each entity. Fuzzy logic rules could now be applied to any problem, as illustrated by the following example.

5.6.3 Illustrative application to a hypothetical pump station problem

Consider an unwanted object arriving in the sewage stream at the pump station. It might lead to blockages or mechanical failures. The significance can now be ranked. Fuzzy sets describe the degree of membership for each entity and this membership was multiplied with the degree of membership of the sub classes, giving each entity in the class overflows a value. This method could be explained with the IF statements: IF (blockage due to unwanted object) THEN (6 x 4) = 24; IF (mechanical failure due to unwanted object) THEN (1 x 5) = 5. This indicates, for example, that the unwanted object causing a blockage is 5 times more significant than it causing a mechanical failure. If a mechanical failure were to occur a back-up pump would take over, or the sump level alarm would trigger a standby mobile pump unit to be employed in a relatively short period of time. However if a blockage occurs at the SHD at in the inlet to the pump station, an overflow will occur in a relatively short period of time without warning.

5.7 Discussion and further work

The framework of the four O's for sewer pump station problems is a basis from which to derive more advanced decision support tools pertaining to sewer pump problems. The concept of fuzzy logic could subsequently be extended to all four O's and the degree of membership should allow for individual entities to share membership between different classes and sub-classes. This extension would necessarily entail advanced software application and the personnel who understood how to operate this.

Presuming that pump problems could be optimally ranked in this way by an advanced decision support system, each problem ultimately needs to be addressed by a responsible person. The derived framework would ideally also aid future communication between different staffing levels (or stakeholders) in terms of pump station problems. Blanksby et al. (2011) noted that, by focusing on tasks and roles in framework development, the different stakeholders are able to cut through major barriers to communication. These aspects could be incorporated into the framework of four O's by identifying specific tasks and roles pertaining to each problem entity, each sub-class and to each class. This would delineate individual roles and responsibilities, which in turn would minimise or mitigate pump station problems in the long run.

The application of genetic algorithms to optimise fuzzy sets for sewer pumps at a single pump station was achieved by Ostojin et al. (2011). Their work shows that a thorough foundation and fuzzy-based framework could lead to the application of advanced techniques in terms of decision support and ultimate optimisation. The next step in terms of local research on this topic would be to derive a decision support tool to link the problems experienced at pump station in general and the framework presented here to possible solutions, allowing for optimisation to minimise the problems. Such an optimisation exercise would of course be purely theoretical and site-specific in the early stages of development. Ultimately it is hoped that the research would culminate into practical solutions and improved sewer services to all urban consumers.

6. DEVELOPMENT OF SEWPUMP SOFTWARE TOOL

6.1 Product development – two alternatives

6.1.1 Data collection and pump station site visits

A number of site visits to existing sewer pump station installations was fundamental in gaining the knowledge regarding the problems experienced. The project team was led by Stellenbosch University. The University of Johannesburg and Engineering Consultants BKS (now AECOM) were involved as collaborating institutions. The site visits were divided between the parties geographically and included selected municipalities in the Western Cape, Gauteng, KwaZulu-Natal. The site-visits were reported on in detail as part of this project's progress, but comprehensive presentation of the findings from each visit were considered beyond the scope of this report.

Initially it was hoped that data gathered from these site visits would be useful for analysis, to obtain a correlation between some parameters. However, such efforts were fruitless and the qualitative knowledge gained focused on identifying and understanding problems and operator needs in line with the development of useful output from this project. This knowledge was built into the final products. These visits and the knowledge gained in the process were fundamental in shaping the final software output.

An information sheet was compiled for each pump station, describing the pump stations in terms of its basic characteristics, operation and maintenance, and problems. The same sheet was used for each pump station visited to ensure consistency as far as possible. Appropriate photos were taken and organised during the visits – as presented in an unpublished deliverable of this project.

The data – and derived knowledge – gained during site visits was used in developing the SewPump tool, presented as part of this project's final deliverable. Two concepts were initially developed into workable software products. Both were aimed at gaining input from possible interested parties. The two tools were called "Pump station DST Tool" and "PAT Tool" and were purposefully developed with different aspects, functionality and appearances. This section provides a brief background to explain the development.

6.1.2 Pump station DST tool

The idea for the sewer pump station decision support tool, SewPump, was founded on the knowledge gained in the early stages of this project. The initial tool was aimed at providing knowledge regarding design and problems in two separate menus.

The initial tool was split into the following two components, discussed below, and later formed the basis for the development of SewPump:

- Design aid: The design aid section allowed the user to view the different sections of a pump station with different design options in each section with aids such as drawings or photos of existing examples in the field. The design section also presented additional literature to aid with further research.

- Problem aid: The problem aid section helped the user to identify problems. The 4 O's were used in the DST to classify problems. The user could select one of the four O-problems and the causes of the problems were presented.

The idea of the SewerAID (Van Dijk et al., 2010) formed the basis of the pump station DST and its development. The tool would act as a visual aid for sewage pump stations, providing useful information in a structured and convenient way. The aim was to keep the tool uncomplicated with limited inputs and maximum output provided in a structured way. The DST provides background information, photos and additional literature to aid with the understanding of sewage pump stations and related problems.

An interactive DST concept was developed as part of this research project to assist with pump station design and understanding. This allowed the user to focus on any particular section of the pump station by clicking on an image. Different components such as the inlet works, sump, pumps, electrical equipment and structural elements were integrated. The tool featured the different sections of a pump station, providing various design components, related problems, literature resources and part descriptions. The tool could be used as a sewage pump stations problem identification tool, but no functionality to actually record information regarding problems was included.

The tool was initially developed in MS Excel, with visual basic macros and related applications. The tool included no user inputs, apart from clicking to obtain the required output text and photos, and no mathematical calculations were required in the process.

The most useful aspects of the tool reported in the feedback session(s) were:

- Visual aids (photos) and additional literature for further reading.
- The fact that the tool could be applied as a basic training tool (for operators as well as managers) was well received and it was clear that this aspect should form a central theme in the final tool.
- Classification of problems according to the 4 O's.
- The problem-aid was deemed more useful than the design aid, mainly because operators could use the problem aid as a training tool; the design aid was aimed at engineers and designers, who would arguably never use such a tool for design purposes.

Subsequent to feedback, the aspects of the tool that would not form part of the ultimate tool, were:

- Despite various compliments on the use of the MS Excel macros to develop the tool, HTML was the preferred scripting language to be used for development of the ultimate tool, SewPump; MS Excel macros were not an option for further development beyond the initial trials
- The lack of user input – limited the application of the tool; some type of user-input would be needed.
- Design aid was not needed.

6.1.3 PAT

A pump station analysis tool (PAT) was created in HTML with Javascript to aid users with making decisions and flagging potential problems pertaining to sewer pump station design, operation and maintenance. A web application was chosen as it was a simple enough application and could easily be linked from another web page, without downloading and installing on a local computer. It was decided to use jQuery (jquery.com) as a JavaScript library since a lot of the code had already been written for in this library, for instance the use of Tabs.

Initially PAT had one function in mind – this was to take parameters from a user and process them. The results would be visually displayed. It was considered appropriate to maintain a very basic visual presentation for PAT (black and white with simplistic icons), with the idea of improved graphic design only with the final stages of development.

A pump station was logically broken up into 5 sections in PAT and these were linked in an ad hoc way to the possible problems:

- Sewage flow rate
- Solids handling devices
- Sump
- Physical parts of the Building (civil, mechanical and electrical)
- Rising Main.

Design and analysis tabs were included where parameters could be entered and information processed. The option was to extend on this functionality later as deemed necessary. PAT could be considered a decision support tool, based on the numerous input values by the user.

Subsequent to feedback the most useful aspects of the DST tool were:

- The HTML-based scripting, allowing for a stand-alone software product that could easily be developed into a web-based tool while limiting the possible workload at a later stage, subsequent to this project.
- Very basic visual presentation (black and white with simplistic icons) that was maintained in the ultimate tool.
- Some form of user input was useful to involve the user.

Subsequent to feedback the aspects of this DST tool that would not form part of the ultimate tool, were:

- the calculations (e.g. for design purposes) was inappropriate; those who liked it were arguably not supposed to ever use it, while those for whom it was intended did not see the need for it.
- The need was to focus on problems, but in PAT it was hard to identify problems since the tool layout was based on the five "pre-defined" pump station elements. This complex link between "design" and "problem" did not work as well as the more basic idea of the 4 O's used in the DST.

- The name PAT is associated with the acronym for "Pumps And Turbines" and should not be used for the sewer pump tool.

6.2 Feedback on alternatives and software specification

6.2.1 WISA2012 Workshop Summary

The Water Institute of Southern Africa (WISA) held its biennial conference at the Cape Town International Convention Centre from 6-10 May 2012. The final number of delegates that arrived on site was 1625, with a total of 1900 registrations processed and the total number of oral papers, workshops and posters was 350. WISA was considered the ideal venue to workshop queries regarding sewer pump problems and the tools forming part of this project.

Workshop 22 entitled, "WRC – Practical application of research: A Tool for sewer pump problems" was hosted by the project team at the WISA2012 conference as part of the formal conference programme. A total of 28 delegates actively attended the workshop, with more than a third of them being from a few large municipalities, including mainly Ekurhuleni Metro Municipality and the City of Cape Town. Most of the feedback gained came from the Ekurhuleni staff. Two notable groups of delegates who also actively took part in the discussions were from engineering consultants and students.

The approach was to gain an in-depth understanding of the participants' views regarding sewer pump problems. The workshop was split into two sections:

(i) a presentation by the research team of both tools (DST and PAT) to provide the necessary background and initiate a focused discussion and

(ii) a discussion session with the workshop focus group, with the research team minuting all comments.

This approach was more productive in terms of the time required than conducting numerous individual interviews. Other studies have noted how group dynamics could work synergically to bring out information (Carey, 1994) and also that participants have more confidence to express their honest feelings within a support group of peers than in individual interviews (Folch-Lyon & Trost, 1981).

The delegates discussed various aspects of sewer pump problems, pump stations, and the intended tools being developed as part of this study. The two tools, PAT and PAID, were presented to the group prior to the discussion to gain specific feedback regarding both tools. The feedback provided was grouped into general comments and those pertaining to the software tools.

6.2.2 Stakeholder feedback: General

During the discussion a few specific areas of general concern and/or interest were identified. Each of these is presented below with notes regarding the feedback from the workshop delegates:

- There was a need for in-house training of municipal staff as well as training material to be used for this purpose. Consultants agreed that it would be useful, but were not as serious about this matter. The matters arising were soon noted to be beyond the scope of this project, but were recorded here to ensure a comprehensive workshop report. Municipalities in particular noted that they would have liked to have staff trained in-house on the use of tools (such as these developed during this study) and also regarding general pump station maintenance and operation. The intention was not to conduct or provide for the education of staff, but rather to give a quick "crash course" during a one-day in-house training session, preferably carrying CPD points. The idea was that somebody could present these workshops free of charge. In addition it was noted that the session would have to be presented on-site (at the municipality) with practical examples and applications pertaining to the particular municipality's pumps stations. Clearly the need extended beyond this project and its scope, and pointed towards either of the following two facets (i) a broader need for further education of existing staff, or (ii) current technical problems that needed to be resolved. Based on the discussion as a whole it could be argued that what was really needed was for the municipality to (i) train staff or (ii) appoint an engineering consultant to address the problems at hand, or to appoint a suitably educated staff member to do so in-house.

- During the session it became clear that very few of the delegates were aware of formerly developed products available via the WRC web site on sewer systems and sewer pumps, including the recent SewerAID (DVD) tool, designed to address the need for self-help in-house training as outlined above. Reference was made by the project team to two former studies pertaining to sewer systems and many of the delegates appeared "surprised" that such products existed and were available free of charge. The WRC web site was promoted for downloading of the products during the workshop. Two questions were posed to the group to probe the use of the WRC document download system. Only staff from Ekurhuleni and Cape Town municipalities indicated that they were aware of the system, and had used the system to download documents. There seems to be a clear disconnect between available knowledge and the need for knowledge. The WRC web site should be promoted at local authority level, coupled with a small workshop to help interested parties use and understand it.

- Time and human resources. The problem of finding time in a busy work schedule to obtain and work through "such material" (WRC reports and available tools) was noted. The conclusion was that a tool should be simple and very easy to use with immediate added value.

- When asking about problems at the pumps, a few delegates noted unwanted products in the system and particularly clogging of rakes, bars, screens and baskets, to be a problem. This confirmed earlier findings in this study during site-visits. It was often hard during the workshop discussions to distinguish between whether these were basic solids-clogging-problems, or sump overflows that were induced by under-sized sumps in relation to the flow rate. Some managers noted the high frequency of pump station maintenance – and particularly cleaning of screens and baskets – to be a problem. The typical frequency of cleaning non-automated solids handling devices was reported to be between one and two visits per pump station site per day in areas with a high solids load in the sewage stream.

6.2.3 Stakeholder feedback: Software products

As part of the workshop, delegates were requested to comment on the PAT and DST as alternative outcomes to this project. The feedback from the workshop delegates pertaining specifically to the software tools is presented below:

- Relating to the general problem of training, the general feeling was that the tool(s) developed as part of this study should be fashioned for self-help training of municipal staff. It was clear that the desired end-product would be uncomplicated and aimed at pushing knowledge out, instead of it being used (or misused) as a decision support tool in the design office.

- Matters that came up were often practical in nature, and the idea was for the tool to address these in an easy way so that staff could use the tool to learn whether a particular state of events could be considered problematic or not. Consider for example: "The tool should tell me how often we should clean the screens/baskets at the pump station" (from the viewpoint of those trying to maintain the system this would be useful to guide them with knowing whether their current habits were normal, or abnormal as opposed to other places). A follow-up question was "Is a frequency of cleaning twice per day acceptable, or is something wrong?", or, "How often should we expect our staff to attend to the cleaning of screens/baskets?" (from the viewpoint of managers who were concerned about staff spending too much time and effort on the matter). The tool should address these basic issues.

- In reply to whether calculations were needed in the software tool the response was mixed. Students all liked the idea, but those in practice felt that calculations should be limited to "basic check lists" such as "Is the pump sump regularly overflowing?"

- Adding calculations to the tool would add a need for user input and would thus increase complexity, room for error and misuse of the tool. This was a particular concern, particularly in view of the discussions about a need for staff training. The suggestion was made that the tool should "include static calculations" – say by providing current guidelines (on pump sump size; frequency of cleaning screens; sewer flow rate and so on) in the form of a single graph that could be "used to read off the answer". The students who were present all liked the idea of having a tool that would do all the calculations (including design), but the municipal representatives and consultants felt uncomfortable with the idea of equipping their staff (and consultants) with what was noted to be a "mock design tool", if developed.

- The conclusion was that the tool should be user-friendly, very easy to understand, simplistic, fashioned to push out existing knowledge without scope for changing parameters and "fiddling around" with it too much.

6.3 SewPump tool

6.3.1 Development

A software tool was subsequently developed. The name SewPump tool was chosen and was derived from word play with "sew..." (sew: mend or repair...; arrange something in an acceptable way); and "sew..." being the three leftmost characters in the word "sewer".

Blanksby et al. (2011) noted that, by focusing on tasks and roles in framework development, the different stakeholders are able to cut through major barriers to communication. It was clear that, with clever planning, SewPump could also be used to cut through communication barriers between different staff levels. It was noted during site visits that there was a need to address communication between pump station operators and their respective managers. The research team set out to develop a tool that would address the concerns and needs (based on feedback on DST and PAT) coupled with a method of communication between operators and technical management.

A software developer was employed to develop a tool with the following broad specification:

- Identification: Help to understand and identify problems at sewer pump stations
- Communication: Facilitate communication between pump station operators and management
- Training: Should transform to a training tool that could be used by individuals for self-study and by managers to facilitate training.

The SewPump tool could be seen as a transformer, with three facets or functioning modes for (i) training (ii) operators and (iii) managers. The mode is selected by clicking a button on the home screen.

6.3.2 Training mode

SewPump opens in the Training mode. The pump problems are arranged according to the 4 O's, and selection of any problem will bring up an InfoBox on the left of the central screen area. The training mode has no functionality other than viewing information, so the box on the right of the screen was applied to provide additional training material from the Wikipedia free encyclopaedia online. In the InfoBox the user is able to click on the information icon to open a one-page PDF InfoSheet that could also be printed for reading away from the computer.

The training mode is well-suited for newly appointed staff and need to learn about sewer pump stations and related problems. Note that the check boxes alongside the list of problems in the central area are inactive.

6.3.3 Operator mode

The operator mode is intended for operators who would like to identify problems at particular pump stations. This is done by clicking on the list of pump station names in the drop down box (top right). Note that this list is supposedly uploaded by the manager, but could also be uploaded by an operator. After selecting the pump station in question, the relevant problems can be ticked by marking the check boxes alongside the list of problems in the central area of the screen.

After completing this task the information is saved, thereby creating a log of problems. The problem log appears on the right of the screen. Initially this list is empty, but with time it will be populated with the data from each report.

The operator can easily email one small file to his manager, who could upload the data to SewPump.

6.3.4 Manager mode

The manager mode enables the viewing of the problem log that was created by the operator. The manager's screen also includes some information regarding uploading information to SewPump (such as pump station names, photos of pump stations to aid identification). The manager is now able to quickly see which pump stations were reported on most recently, or of course to identify which were infrequently visited – and reported on.

The manager is unable to uncheck a problem. Thus, if the manager and operator cannot agree on what type of problem is occurring at a particular pump station it would encourage conversation or even better – a site visit to the problematic pump station. When the operator agrees that the problem was resolved (or incorrectly identified) it could be unchecked again by the operator.

Sewpump will be particularly valuable for those who use it for a relatively long period of time, thereby creating a useful log of problems for all pump stations over a number of years.

The project team would like to encourage any municipalities with the necessary resources to use SewPump and in doing so to improve the condition of their sewer pump stations. Also, while doing this to log any problems encountered over a time period that could be added to the list for future research into pump problems. The SewPump log would form an ideal input to other related tools, such as the risk-based prioritization for pump station decommissioning discussed earlier in this report. SewPump was designed as an off-line tool, but it could be upgraded with web-based functionality in future if the need arises.

7. CONCLUSION

7.1 Project overview

7.1.1 Relevance

Pumps are essential components in most sewer systems and are often considered by operators and managers to be the most problematic. The project sets out to address a number of pertinent issues with regards to sewage pumps, pump stations, and related elements of sewer systems.

South African sewer systems and storm drainage systems are designed as separate systems. The sewer is traditionally waterborne. Waterborne sewers (also called conventional sewers) use water as the mode of transport for excrement and other waste. This research project focused exclusively on separate waterborne sewers and specifically on decentralised sewerage pumps and related infrastructure in the piped sewer system; wastewater treatment and pumps used in the treatment process are thus excluded per definition.

The issue at hand extends beyond hydraulics and design criteria to enable stakeholders to support decision-making and communication. The aim was to link decisions to problems occurring at sewage pump stations during normal operating life, after commissioning. One of the key issues addressed by this research and the subsequent software tool revolves around improved knowledge transfer and communication between different levels of technical staff involved with sewerage pumps.

7.1.2 Motivation

This project was motivated by the general lack of published research into sewer pump stations and related problems, combined with the need for such knowledge during the planning, modelling, optimisation, design, operations and maintenance phases of these infrastructure elements. A recent WRC project culminated in a design guideline for waterborne sanitation (Van Vuuren and Van Dijk, 2011a) as well as a guideline addressing operation and maintenance of these systems (Van Vuuren and Van Dijk, 2011b). One of the outcomes of the former project was a product called SewerAID – a DVD providing background on various matters pertaining to waterborne sewers as a whole. Findings from their studies pointed to critical research needs with regards to sewer pump stations and related problems.

Subsequent to the work by Van Vuuren and Van Dijk (2011a; 2011b) a need remained to assess various aspects relating to sewerage pumps and related problems in more detail, backed by data from the field. A lot of experience over the years has been gained based on practical considerations, particularly as it pertains to local conditions and the eventual problems that have been "solved on-site" by operators and technical staff responsible for operating sewerage pumps. This research project also allowed for the review, capture and dissemination of such knowledge.

7.1.3 Key objectives

The key objectives of this study were to: conduct a knowledge review of sewage and pumps; select or derive a classification system for sewerage pumps and related problems; conduct field work and data collection to determine the types of problems typically experienced during the operation of sewerage pumps and the possible causes and to better understand these problems; analyse the field data in order to extract useful information; develop a practical software tool intended as a training and communication tool regarding pump station problems; report a select portion of the research by means of a peer reviewed journal article; report on all the above knowledge and findings as the final deliverable report. The list above provided direction and actions required to address these issues were the main drivers of the project.

7.1.4 Sewage and solids

Sewers operate over a wide range of flow rates and the limiting values need to be taken into account when evaluating how effectively a sewer will transport solids to a pump station. Effluent velocity at the various flow rates is the most significant factor influencing the transport of solids through a sewer. The content and relative contribution of solids type to the total solids varies from one catchment to another and is influenced by the flow rate in various ways, but the total solids mass is proportional to the sewage flow rate.

A distinction needs to be made between the solids that can be transported through a sewer in terms of their specific gravity relative to that of the effluent, whether or not they will disintegrate with time and their impact on the operation and life of pumps. As the clogging of pumps by material that had a specific gravity similar to that of the effluent was a problem and little literature on the subject could be found, a series of laboratory experiments was done to determine the effectiveness of screening baskets in removing these materials. Recommendations for the location of screening baskets relative the effluent levels in the sump where they are to be placed were made and the need for further research in this regard was noted.

7.1.5 Problems and causes

Identifying, listing and classifying the problems and how the measurement of the intensity or extent would be quantified was a particular challenge faced by the research team. The term “problem” is used loosely in this research project. A clear distinction needs to be drawn between problems and their causes. If the underlying causes are not identified and addressed, the problems will keep occurring. This study could be considered as one addressing problems (direct) versus the underlying causes (indirect). The effort at addressing the problem at a sewer pump could be distracted from its focus by tracing the problem back to the underlying cause. These underlying causes may have to be considered as the actual issue to be addressed. However, the emphasis here was to address particular problems relating to pump stations in the most direct way possible at the pump stations.

During the problem identification phase of the project it became apparent that boundaries had to be established to prevent the proliferation of problems and their causes that were beyond the scope of the study. A problem was therefore limited to an issue that could be determined by means of inspection at the pump station site, discussion with the operation and maintenance staff, or by reviewing documentation covering problems.

A comprehensive list of common problems was compiled from literature, site visits and stakeholder interviews during this research. The listing by Van der Merwe-Botha and Manus (2011) and Sidwick (1984) of some common problems relating to sewers and pumps is the only local peer reviewed report of this nature that could be found during the knowledge review. In this study problems at sewage pump stations were identified following an in depth literature study in conjunction with a combination of field visits and stakeholders interviews at selected sites in the Western Cape, Gauteng and KwaZulu-Natal.

Sewer pump station problems were ultimately categorized into four classes. Each direct problem identified in the first phase of the project could ultimately be placed into one (or more) of these four problem classes, based on a degree of membership to each class. In presenting the framework here, aspects regarding roles and responsibilities were not included, so as to maintain the focus. These could be an obvious future extension to the framework presented here. The four classes ultimately arrived at were coined the 4 O's of sewage pump station problems, namely: overflows, odours, operational (maintenance included); other. These four classes were described by explanatory tree diagrams and formed the basis for the items listed in the SewPump tool.

7.1.6 Stakeholder workshop

The Water Institute of Southern Africa (WISA) conference, WISA2012, was considered the ideal venue to workshop queries regarding sewer pump problems and the tools forming part of this project. A workshop entitled, "WRC – Practical application of research: A Tool for sewer pump problems" was hosted by the project team. The approach was to gain an in-depth understanding of the participants' views regarding sewer pump problems and the software tool. The feedback from the workshop was incorporated to the final development of SewPump.

7.1.7 SewPump tool

SewPump was aimed at providing information regarding sewer pump problems. The tool was developed to act as a visual aid for staff involved with the operation and management of sewage pump stations, thus providing useful information in a structured and convenient way. The aim was to keep the tool uncomplicated with limited inputs and maximum output.

It was clear that, with clever planning, SewPump could also be used to cut through communication barriers between different staff levels and it was extended to address that need. It was noted during site visits that there was a need to address communication between pump station operators and their respective managers. The same was reported during the WISA2012 workshop. The research team set out to develop a tool that would address the concerns and needs (based on feedback) coupled with a method of communication between operators and technical management.

A software developer was employed to develop an html-based stand-alone software tool with the following three main focus areas: Identification (help to understand and identify problems at sewer pump stations); communication (facilitate communication between pump station operators and management); training (a training tool that could be used by individuals for self-study and by managers to facilitate training). The SewPump tool is available as a stand-alone product and is attached to this report as a CD.

7.2 Epilogue

Two aspects need to be understood when referring to sewage pumping, namely the pump station (infrastructure and equipment) and the sewage stream to be pumped. This research project included a review of both these aspects. It was concluded that both were well documented, based on former research. However, previous publications regarding solids in sewers and their behaviour was limited, particularly with regards to baskets that were found to be very common in local sewage pump installations. Limited laboratory tests were conducted to investigate the inter-action between solids in sewage and screening baskets.

This project entailed numerous site visits to sewage pump stations, aimed at gaining information from the field and learning about the practical matters pertaining to the daily operation of sewage pump stations as well as related problems. A workshop was organised at the WISA2012 conference, where feedback was gained from the delegates regarding sewage pumping and the proposed tools developed by the project team. The team concluded that operators and managers alike see sewage pumping as a problem; one of the key concerns noted during the site visits and the workshop was the poor communication between technical managers and operators.

A tool was developed as part of this project that would: (i) aid operators with sewage pump problem identification so as to help understand and identify problems at sewer pump stations; (ii) facilitate communication between pump station operators and technical management and (iii) provide for basic training regarding sewage pumping and related problems that could be used by individuals for self-study and by managers to facilitate training.

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