# A Multi-criteria Selection of Water Treatment Solutions for Rural African Villages. A Case Study of Makwane Village

**By**

**Tresor Mosigo Bumba**

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**Tresor Mosigo Bumba**
**29302693**

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**Tresor Mosigo Bumba**

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|---|---|
| Supervisor: | Dr Olufemi Adetunji |
| Department: | Industrial Engineering |
| University: | University of Pretoria |
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# Foreword

The journey to completing this project has been both enlightening and eye opening. It is my hope that the results of this work are applied to solve some of the water related problems in rural Africa. I would like to thank my wife Judith, my mother Maggy and my Supervisor Dr Olufemi Adetunji for their encouragement and support.

# Abstract

The availability of water can be considered as one of the key ingredients to the human life, yet this resource remains scarcely available to those living in the rural parts of Africa. When water does present itself, it is often impure and requires extensive treatment. Water treatment systems, particularly those capable of treating water in rural areas, are currently areas of research and entrepreneurship focus, making a number of potential solutions available, and other still coming in. Unfortunately, these systems are not always capable of performing in particular socio-cultural and economic contexts, or are often deployed in the wrong rural areas. Therefore these systems do not perform at their optimal level of design.

Rural areas in Africa have different socio-cultural and economic context from each other, and this needs to be taken into account if one is going to select the right water treatment system for a particular area. Using industrial engineering tools, two water treatment system selection models; an Additive Analytic Hierarchy Process model and a Fuzzy Logic based model, are presented and then integrated. These models take into account the context of selected rural area by pitting available water purification systems against selected criteria to determine if it is the right fit for the rural area considered. Both models are then pitted against each other to determine which is more adept at selecting the appropriate water purification system. Three water treatment alternatives were considered after an analysis was conducted on the available solutions on the market. The water treatment systems under consideration were the Biosand Filter with Zeolites (BSFZ), the Silver Impregnated Porous Pot, and A Borehole system.

Makwane, a rural village in Limpopo, South Africa was used as a case study to demonstrate the application of the selection models. The BSFZ was selected as the ideal water treatment system to be implemented in Makwane

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

## 1.1. Background and Motivation

During the United Nations Millennium Summit in 2000, the international community reached an agreement to halve, by 2015, the proportion of people who did not have sustainable access to safe drinking water, and extend access to 88% of the global population (WHO/UNICEF, 2012). In 2012, the World Health Organisation (WHO) and the United Nations Children's Fund (UNICEF) Joint Monitoring Programme for Water Supply and Sanitation reported that 89 % of the world's population (approximately 6.1 billion people) already used improved drinking water sources between 1990 and 2010. Although tremendous progress has been made, achieving 1% point more than the Millennium Development Goal (MDG) target, the WHO/UNICEF report (2012) also pointed out that 780 million people still have no access to safe drinking water worldwide. This group of the population is currently living in developing nations and the worst scenario has been particularly reported in Sub-Saharan Africa where this region still faces great challenges in increasing the use of improved drinking-water. According the WHO/UNICEF report (2012) this part of the world accounts for more than 40% of the global population without access to safe drinking water. This implies that close to 50% of the sub-Saharan African population still depend on untreated groundwater or surface water sources as their daily source of drinking water supply.

In the year 2000, a report by WHO/UNICEF, revealed an estimated 2 million deaths occurred annually as a result of waterborne diseases such as diarrhoea (WHO/UNICEF, 2000). Baumgartner and co-workers (2007) pointed out that an estimated five million people lose their lives due to water-related illnesses every year. In South Africa, for example, there have been a large number of outbreaks of cholera, typhoid fever, salmonellosis, shigellosis, gastroenteritis and hepatitis linked to contaminated drinking water (Department of National Health and Population Development, 2001; Department of Health, 2005). Cholera and typhoid infections have been reported in Mpumalanga, KwaZulu-Natal and the Eastern Cape since 2000 (Department of Health, 2005).

Contaminated groundwater in Delmas, in the Mpumalanga Province, caused a month-long health crisis. While the official report claimed a total of 3 000 people with diarrhoea, 561 with typhoid infections, and five deaths in 2005, the community pointed out more than 49 deaths were due to typhoid and diarrhoea (Groenewald & Dibetle, 2005; Masinga, 2005). These figures indicated the extent to which lack of safe drinking water can be detrimental to human health. It is, therefore, important for Sub-Saharan African nations to find cost effective means of providing safe drinking water to rural communities.

To prevent outbreaks of waterborne diseases and protect public health in rural communities, two approaches have been considered. These include: centralised drinking water supply, and decentralised point-of-use (POU) systems. The latter systems are particularly useful in geographically isolated areas, where centralised water networks are not feasible. There is conclusive evidence that household water treatment systems (HWTSs) are capable of dramatically improving the quality of drinking water, and may therefore, provide a short to medium term solution for meeting the basic need of safe drinking water in rural communities (Sobsey, 2002; Murcott,2006, Mwabi et al., 2013). Furthermore, HWTS can make an impact with regard to reducing the number of waterborne diseases in rural communities. A study by Tshwane University of Technology has shown a number of household water treatment devices that are considered to be reasonably priced for low income households (Mwabi et al., 2013), and can therefore be used to produce safe drinking water in developing areas. These include the biosand filter with zeolites (BSFZ), and the silver impregnated porous pot (SIPP).

Though HWTSs provide a low cost and suitable avenue for the purification of water, it is essential that, in the long term, a centralized piped system is designed and installed in rural areas. Although the implementation of centralised systems, such as piped systems, is complex and often too costly for the local authority, these will not only bring clean water to rural communities but, they will also serve as a catalyst to push these communities in to the 21st century.

There are numerous HWTSs available for implementation in rural areas. What is lacking is a scientific approach that helps with the selection of appropriate HWTSs given the particular geographical and socio cultural social cultural context of the selected rural African community.

## 1.2. Problem Statement

In most African countries, unsafe drinking water supplies are found in rural communities that are commonly scattered; these also include informal peri-urban communities that are continuously expanding. In these communities, groundwater remains the main source of water. There has also been successful implementation of treatment systems on a limited basis. What is currently required is a systems approach to guide the evaluation and selection of appropriate water treatment systems given the socio-cultural and economic context of the rural African village where implementation is slated to take place. This program must clearly articulate the steps needed for identifying, evaluating, and selecting a viable HWTSs for the selected rural setting.

## 1.3. Aim

The aim was the development of systems approach for the selection of appropriate water treatment solutions for rural African countries given their socio cultural and economic context and the constraints of the stakeholders. Makwane Village, a rural community situated outside Roosenekal in the Limpopo Province, was selected as a case study. This village has only one water supply source, which is currently groundwater. Results from this case study could be extrapolated and configured for use in other rural areas of Africa, especially those that depend on groundwater sources. The proposed study seeks to further the research on rural water treatment systems by providing the process steps required for the development of a suitable evaluation and selection model for water treatment systems, using a number of criteria to decide which choice/s should be made for a locality based on the peculiar characteristics of the area. There are numerous HWTSs available in the market that could alleviate the challenges facing rural communities in terms of safe drinking water. To evaluate and select the ideal drinking water treatment system for a particular community, the following factors were analyzed:

- The affordability of the treatment system under consideration to donors/government
- The risk the treatment system under consideration presents in its operations
- The social impact and accessibility of the treatment system in the selected rural area
- The effectiveness and efficiency of treatment system

Though there is much research going into technologies to make water systems available to many communities in underdeveloped countries, there remains little effort into how to select the appropriate treatment system given the different options that are being developed, and the particular economic-socio-cultural system of the societies in need. The dominant aim of the study is to provide an appropriate evaluation and selection model for policy developers and implementers.

## 1.4. Study Objectives

To achieve the aims of this study, the following objectives were pursued:

- A comparative breakdown of the supply chain process that would be used to deploy the HWTSs under consideration at Makwane Village. This included all supply chain costs as well as the processes required for effective and sustainable implementation.
- Analyses of the opportunities for onsite production of the HWTS, and job creation.
- Social impact and accessibility analysis of each HWTS under consideration
- Comparative evaluation of two multi criteria selection techniques that were used to select the most appropriate HWTS.

## 1.5. Study Design

The study included four stages. The first stage pursued a demographic study of Makwane village. The second stage analyzed the HWTSs available in the market capable of delivering safe drinking water to Makwane village in particular, three treatment systems were selected at the end of this stage. The third stage of the study analyzed the selected water systems according to selected criteria. Finally two MCDM models were developed to help select the appropriate for deployment at Makwane

The geographical, socio-cultural and economic underpinnings that governed Makwane were analysed. This included a demographic study of Makwane village as well as a look at the processes the community used to collect water and what activities this water was used for. The outcome of this study was to determine user needs

After the pre-selection stage two HWTS were identified for further analysis as well as a borehole system. The bio-sand water filter with zeolites (BSFZ) and the silver impregnated porous pot (SIPP) were being manufactured at the Council for Science and Industrial Research (CSIR). Both HWTSs had been patented by the South African government, therefore easing the problems that may arise during the mass production and distribution of the devices.

All activities regarding the construction of these devices were analysed and documented, including the sourcing of input materials, manufacture, storage, distribution and logistics. Both treatment systems were developed and configured by the Tshwane University of Technology Water Research Group (TUTWRG).

Concerning the centralized treatment systems, focus was limited to the analysis and design of a ground water source. A thorough analysis of past and current research was conducted using available journals articles and contact sessions with engineering professionals who had experience with designing, implementing, and operating ground water treatment systems.

The SIPP, BSFZ and the borehole system was analysed with regard to affordability, risk, social impact and accessibility and product effectiveness criteria. Each of the stated criteria was allocated metric/s that helped focus the analysis into them in greater detail.

Two Multi-Criteria Decision Making (MCDM) models were developed, using affordability, risk, product effectiveness and social impact and accessibility as criteria. These models were used to help with the selection process of the BSFZ, SIPP or borehole system as the optimal water treatment method. Both MCDM models were then evaluated to determine their effectiveness in selecting the appropriate HWTS.

## 1.6. Material and Methods

The following tools were used during the course of the study to help us achieve our aims.

### 1.6.1 Process Modelling

The key objective of process modeling in this proposed study was to allow us decompose processes in order to evaluate criteria metrics. These processes included material sourcing processes, manufacturing processes and deployment processes at Makwane village. This exercise was done for the selected HWTS and borehole system. The Standard Business Processing Model and Notation (BPMN) was used. The BPMN provided a graphical format for capturing and modelling the ordered sequence of all activities used to deliver water treatment systems, and supporting information as reported by White (2006). All activities and processes that described how objectives were pursued were documented and modelled using standard BPMN software. These made the comparison of various supply chain models easier as all processes were documented using the same terminologies.

### 1.6.3. Criterion Analysis

The data collected for the MCDM models was linked to each criterion. Metric/s were defined for each criterion, and all data regarding each particular metric was collected and analysed in order to support the decision making process. Each water treatment system was analysed against each criterion. The results of the criterion analysis were used as inputs to the MCDM models.

### 1.6.4 Multi-Criteria Decision Making (MCDM) Models

MCDM models constitute a major part of decision theory and analysis. They are particularly useful in circumstances which necessitate the consideration of different alternative actions which cannot be evaluated by the measurement of a single, simple dimension. The initial MCDM model selected was AHP. Both the additive and multiplicative AHP models were used to model the decision making process. This was due to the simplicity of the models and its ability to rank, in order of importance, the criteria used to select the most appropriate treatment system for Makwane. The AHP models were also used to help determine, in the form of ranking, the most favoured treatment system. The outcomes of the additive AHP model, particularly the range of values for each of the criterion were applied to the fuzzy logic model.

The AHP model uses a linear grading model to determine which treatment system is most preferred. The Additive and Multiplicative AHP are improved versions of the original AHP that addressed the problems stated, especially the grading of alternatives. The multiplicative AHP uses an exponential scale as opposed to a normal linear scale. An exponential scale was thought to better mimic the thought process of human beings as opposed to the linear grading method of traditional AHP The additive AHP is a logarithmic translation of the multiplicative AHP, this makes it easier to manipulate mathematically.

The development of a fuzzy neuro network selection model provided more value. Fuzzy set theory, as presented by Zadeh (1965), alternatively referred to as fuzzy logic, is concerned with modelling the level of truth that a particular outcome belongs to a particular classification. The degree of importance of a criterion can be quantified within a particular range. The fuzzy logic model centers on the creation of the membership function. The membership functions represent the change of preferences of decision makers (i.e. degree of importance) that decision makers given a certain criteria. A membership function is attained when a preference grade is fuzzified. This is where, instead of entering a single grade, an ordered triplet of triangular fuzzy numbers stated in the form $(a_l, a_m, a_u)$

The ANFIS (neuro network) model resides on the MATLAB toolbox. The ANFIS developed a rules based engine (white box), based on the random application of alpha cutsThe basic structure of a fuzzy inference system is a model that:

*“Maps input characteristics to input membership functions; input membership functions to rules; rules to a set of output characteristics; output characteristics to output membership functions; and the output membership functions to a single-valued output or a decision associated with the output”*

The fuzzy sets (membership functions) of all criteria were used as inputs into the neural network model. An alpha cut of membership function is a set of discrete approximations of a continuous variable. The ANFIS model repeatedly takes different alpha cuts of the fuzzy sets of each criterion and combines them to determine whether each HWTS under analysis falls in prescribed categories

The neuro-fuzzy model allowed for the ranking and classification of any water treatment system, even those that fall outside the scope of this thesis. Every water treatment system can be analysed according to the above mentioned criterion, and then classified relative to other water purification systems.

### 1.7 Study Outline

**Chapter 2** discussed the current state of drinking water in the world and Africa in particular. The millennium development goals (MDGs) and the health and economic effects of consuming impure water were discussed and documented. Various water purification instruments and deployment strategies that could be used to deliver water in rural areas were identified and analysed. Finally, various decision making models that could be used to select the ideal water treatment system for deployment in Makwane village. This chapter also identified the requisite criterion used to analyse various water treatment systems for Makwane village.

**Chapter 3** gave an overview of Makwane village. Population demographic data of the village was analysed to further understand the day to day problems encountered by the residents of this village and their needs.

**Chapter 4** detailed the process activities including material sourcing, manufacturing and deployment, for each of the water treatment systems under consideration that can be used to deliver water to Makwane village. The process maps were used to analyse the performance of each water treatment system versus a particular criterion.

**Chapter 5** used the identified water treatment system and criteria as inputs into an Analytic Hierarchy (AHP) model. A fuzzy decision model was also developed using some of the outputs of the AHP model and the results obtained in chapter 4. The results provided by both decision models were analysed to determine which model worked best in determining the most appropriate deployment strategy for Makwane village.

**Chapter 6** summarised the most salient points in the study, provides conclusions and recommendations going forward.

# Chapter 2

# Literature Review

## 2.1 Introduction

The world leaders increasingly recognise safe drinking water as a critical building block of sustainable development. However, for decades, safe water supply, which is a basic necessity, still remains a treat for millions people in the developing world. Access to a safe, reliable, and affordable water supply is one of the most effective means to improve public health and save lives (WHO/UNICEF, 2012). In contrast, unsafe water and lack of sanitation generate a vicious cycle that obstructs the economic and social development growth of a country. It has been pointed out that, inadequacies in water supply not only affect health harmfully, both directly and indirectly, but also prevent good sanitation and hygiene (Hunter et al., 2010). It is, therefore, imperative to advocate improvements in various aspects of water supply, which represents important opportunities to enhance public health, and subsequently, the social and economic development of a country.

There has been an on-going global effort to promote and provide access to safe drinking water to all. In 2000, the United Nation (UN), as part of its Millennium Development Goals (MDGs), sets a key target 7c, which aims to reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015 (United Nations General Assembly, 2000). In 2003, the World Health Organisation (WHO) launched the Household Water Treatment (HWT) and Safe Storage Network, a consortium of nearly 100 organisations working throughout developing nations. This network aims to promote collaboration, generating research, and exploring measures to scale up pilot projects. The WHO declared 2005–2015 the decade of water, and the goal is to establish the framework to eventually provide full access to water supply and sanitation for all people. On 28 July 2010, the UN General Assembly adopted Resolution 64/292, recognizing that safe and clean drinking water and sanitation is a human right, essential to the full enjoyment of life and all other human rights. The United Nations Member States and international organisations were then called to offer funding, technology, and other resources to help the poorer countries to scale up their efforts to provide clean, accessible, and affordable drinking water and sanitation for everyone (WHO/UNICEF, 2004; Montgomery and Elimelech, 2007).

Remarkable progress has been made to date, with over two billion people gaining access to improved drinking water since 1990, and the Millennium Development Goal of halving the number of people without access to improved drinking water, was achieved in March 2012, ahead of schedule. Nevertheless, an estimated 783 million people still lack access to safe drinking water in communities living in rural areas with low income. A large proportion of this group of the population is currently living in developing nations. The worst scenario has been reported in Sub-Saharan Africa, as this region still faces great challenges in increasing the use of improved drinking-water (WHO & UNICEF JMP, 2013).

Non-existent water supplies or inadequate treatment of drinking water, has led to the exposure of rural African communities to many waterborne diseases due to the poor water quality they consume daily (Venter, 2000; Murcott, 2006; Momba et al., 2006a,b, 2008). It has been reported that an estimated two million people lose their lives each year due to water-related diseases (Baumgartner *et al.*, 2007; Pritchard *et al.*, 2009). There is, therefore, a need to reconsider appropriate household drinking water technologies based on their performance and affordability, and the deployment strategies that may ensure their continual use in the production of safe drinking water in rural communities. This chapter focuses on a review of drinking water coverage trends in Africa, safe drinking water technologies options in rural areas, various stakeholders involved in the provision of safe drinking-water, supply chain design, and decision making.

## 2.2. Access to drinking water in Africa

### 2.2.1 Water sources

Water is an essential resource for sustaining economic development in all sectors. However, there are limited sources of water available to provide clean drinking water to the entire African population. This continent is characterised by an extreme variability in rainfall - in time and space- which is reflected in an uneven distribution of surface and groundwater resources, from areas of severe aridity with limited freshwater resources, like the Sahara and Kalahari deserts in the northern and southern parts, to the tropical belt of mid-Africa with abundant freshwater resources (United Nations Environment Programme, 2008).

In spite of its surface area of about one-fifth of the Earth’s land surface, the combined annual flow of rivers in Africa is only about seven percent of the world’s river flow reaching the oceans. Globally, Africa has been identified as a home to both the largest number of water-scarce countries, as well as a home to the most difficult countries to reach in terms of water aid. The United Nations Economic commission for Africa (2012) has pointed out that one third of all nations suffered from clean water scarcity, but Sub-Saharan Africa had the largest number of water-stressed countries compared to any other place on the planet. As of 2006, out of its 800 million people, an estimated 300 million lived in a water stressed environment. The findings presented at the 2012 Conference on "Water Scarcity in Africa: Issues and Challenges" has estimated that by 2030, 75 million to 250 million people in Africa will be living in areas of high water stress, which will likely displace between 24 million and 700 million people as conditions will become increasingly unlivable (Conference on Water Scarcity in Africa: Issues and Challenges, 2012). In 2008, Northern Africa exceeded their limit of abundant resources, and their sustainable limits for water resources; however, Sub-Saharan Africa was approximately 13 % below the abundance of water resource limits (25%), with a 57% prediction that this area is rapidly approaching their “water scarcity” limit (UN, 2011).

Africa contains approximately 660 000 km$^3$ of groundwater reserves (WHO & UNICEF JMP, 2013). This is more than the renewable freshwater resources contained in African lakes. Communities in rural and low-income peri-urban areas are reliant on groundwater. Pedley and Howard (1997) approximate that as much as 80 % of the drinking-water used in these communities is extracted from groundwater sources. Nearly 1.5 billion people worldwide get their drinking water supplies from ground water sources, this makes groundwater the most extracted raw material at 600 – 1100 km3 per year (Kinzelbach et al, 2003). Approximately 80 % of North-Africa's potable water is provided by groundwater supplies (JMP, 2008). Groundwater is one of the most reliable sources of potable water for rural water supply in Sub-Saharan Africa, where 80% or, approximately 540 million people, rely on ground water supplies (JMP, 2008).

In South Africa, surface water sources consist of dams and rivers, which account for 77 % of the total supply of fresh water, while return flows (sewage and effluent purification) occupy the second position and account for 14 % of the country 's total fresh water sources (Van Vuuren, 2009). Surface water not only serves the communities for agriculture and drinking, but it is also used for a variety of other purposes. These include drinking water for domestic animals (cattle, sheep, goats, etc.), washing of clothes by local residents and even the disposal of human and animal excreta. Groundwater sources, which are comprised of wells and spring water, occupy the third position and constitute nine percent of fresh water sources (Van Vuuren, 2009). This drinking water source provides better accessibility (shorter distance to travel), and is less polluted compared to surface water source.

### 2.2.2 Categories of drinking water sources for developing countries

Drinking water sources for developing countries have been classified as: (a) improved drinking water sources, and (b) unimproved drinking water sources. The term "improved access" refers to households that obtain water from sources that are superior to traditional sources, contrary to unprotected water sources (Van Vuuren, 2009). Water sources that meet the definition of improved water include a household connection, borehole, protected dug well, protected spring, or rainwater collection (WHO/UNICEF, 2004). Based on this definition, the WHO/UNICEF Joint Monitoring Programme for

Water-supply and Sanitation (JMP), which monitors progress on the MDG water supply target (WHO/UNICEF, 2010), therefore, provide three main categories of drinking water supply (Figure 2.1). The number of people using an improved drinking water source increased from 252 million in 1990 to 492 million people in Sub-Saharan Africa during this period (UN, 2011). With its current population of more than 1 billion, the WHO/UNICEF JMP report (2012) indicated that only 66 % of African people had access to improved source of drinking water. Sub-Saharan Africa accounts for more than 40% of the global population who lack access to improved drinking water sources (WHO/UNICEF JMP report, 2012). This implies that close to 50% of the sub-Saharan African population still depend on untreated ground or surface water sources as their daily source of drinking water supply (WHO/UNICEF JMP report, 2012). Estimated figures have revealed that since 1990, 322 million Africans have gained access to an improved drinking water source. Despite this increase in drinking water coverage, the population relying on unimproved drinking water sources has increased from 279 million in 1990 to 344 million in 2010 (WHO/UNICEF JMP report, 2012).

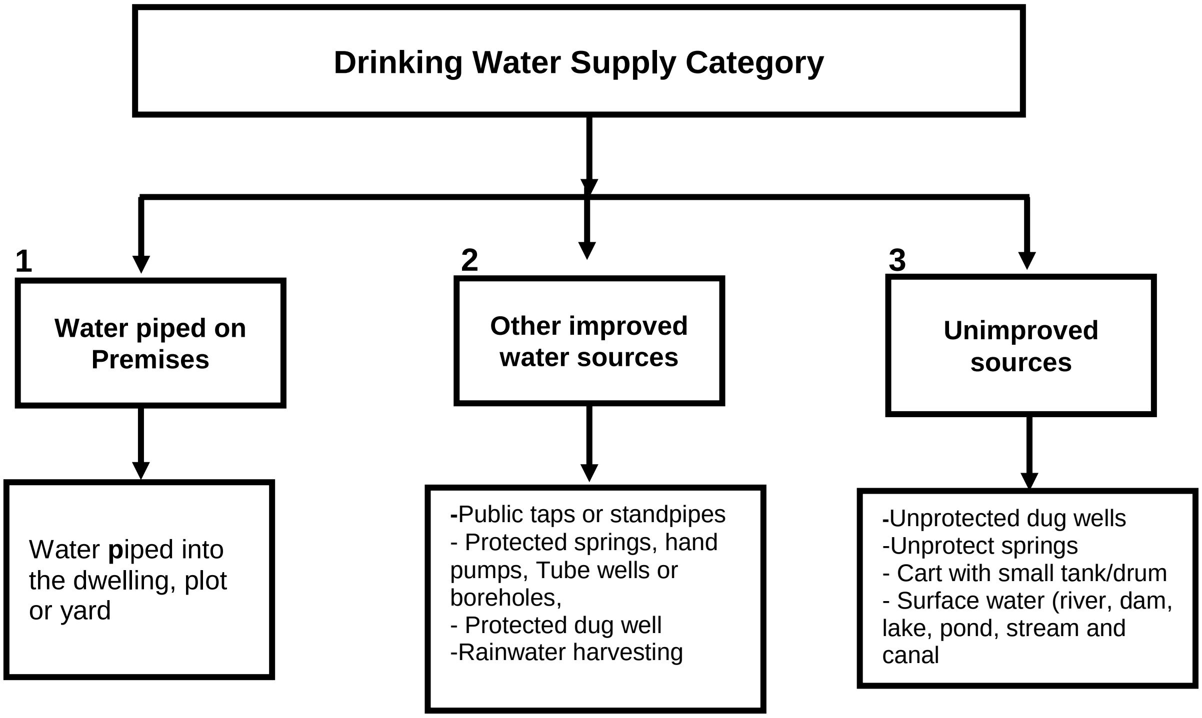


*Figure* ***Error! No text of specified style in document.****-1: Drinking water source categories available to developing countries (adapted from WHO/UNICEF JMP 2010)*

Use of unimproved drinking-water sources in rural areas (46%) was revealed to be threefold that of urban areas (15%) (WHO/UNICEF JMP, 2010). This can clearly be seen in Tables 2.1 and 2.2, which illustrate the profile of drinking water sources in urban and rural populations of the SADC countries, respectively.

*Table* ***Error! No text of specified style in document.****-1: Shape of drinking water sources used in urban populations of SADC countries*

| Country | Year | Water Sources (percentage of population) | | |
|---|---|---|---|---|
| | | Piped | Other Improved | Unimproved |
| Angola | 1990 | 1 | 29 | 70 |
| | 2008 | 34 | 26 | 40 |
| Botswana | 1990 | 39 | 61 | 0 |
| | 2008 | 80 | 19 | 1 |
| Democratic Republic of Congo | 1990 | 51 | 39 | 22 |
| | 2008 | 23 | 57 | 29 |
| Lesotho | 1990 | 19 | 69 | 12 |
| | 2008 | 59 | 38 | 3 |
| Madagascar | 1990 | 25 | 53 | 22 |
| | 2008 | 14 | 57 | 29 |
| Malawi | 1990 | 45 | 45 | 10 |
| | 2008 | 26 | 69 | 5 |
| Mauritius | 1990 | 100 | 0 | 0 |
| | 2008 | 100 | 0 | 0 |
| Mozambique | 1990 | 22 | 51 | 27 |
| | 2008 | 20 | 57 | 23 |
| Namibia | 1990 | 82 | 17 | 1 |
| | 2008 | 72 | 27 | 1 |
| South Africa | 1990 | 85 | 13 | 2 |
| | 2008 | 89 | 10 | 1 |
| Swaziland | 1990 | NA | NA | NA |
| | 2008 | 21 | 40 | 39 |
| Tanzania | 1990 | 34 | 60 | 6 |
| | 2008 | 23 | 57 | 20 |
| Zambia | 1990 | 49 | 40 | 11 |
| | 2008 | 37 | 50 | 13 |
| Zimbabwe | 1990 | 94 | 5 | 1 |

|  |  |  |  |  |
|---|---|---|---|---|
|  | 2008 | 88 | 11 | 1 |

*NA: No data available, Source: WHO/UNICEF JMP, 2010*

*Table **Error! No text of specified style in document.**-2: Profile of drinking water sources used in rural populations of SADC countries*

| **Country** | **Year** | **Water Sources (percentage of population)** |  |  |
|---|---|---|---|---|
|  |  | **Piped** | **Other improved** | **Unimproved** |
| Angola | 1990 | 0 | 40 | 60 |
|  | 2008 | 1 | 37 | 62 |
| Botswana | 1990 | 13 | 75 | 12 |
|  | 2008 | 35 | 55 | 10 |
| Democratic Republic of Congo | 1990 | 0 | 27 | 73 |
|  | 2008 | 2 | 26 | 72 |
| Lesotho | 1990 | 1 | 56 | 43 |
|  | 2008 | 5 | 76 | 19 |
| Madagascar | 1990 | 0 | 16 | 84 |
|  | 2008 | 4 | 25 | 71 |
| Malawi | 1990 | 2 | 31 | 67 |
|  | 2008 | 2 | 75 | 23 |
| Mauritius | 1990 | 99 | 0 | 1 |
|  | 2008 | 99 | 0 | 1 |
| Mozambique | 1990 | 1 | 25 | 74 |
|  | 2008 | 1 | 28 | 71 |
| Namibia | 1990 | 14 | 37 | 49 |
|  | 2008 | 27 | 61 | 12 |
| South Africa | 1990 | 25 | 41 | 34 |
|  | 2008 | 32 | 46 | 22 |
| Swaziland | 1990 | NA | NA | NA |
|  | 2008 | 67 | 25 | 14 |
| Tanzania | 1990 | 1 | 45 | 54 |
|  | 2008 | 3 | 42 | 55 |
| Zambia | 1990 | 1 | 22 | 77 |
|  | 2008 | 1 | 45 | 54 |
| Zimbabwe | 1990 | 7 | 63 | 30 |
|  | 2008 | 5 | 67 | 28 |

NA: No data available (Source: WHO/UNICEF JMP, 2010)

By 2010, reports indicated that only 23 countries in Africa are on track for meeting the MDG drinking water target (WHO/UNICEF JMP, 2012). Overall, the coverage trends of drinking water supply have been dominated by disparities within the regions. In 2010, the trends for unimproved drinking water sources were reported as follows within the regions: Eastern Africa - 126 million, Western Africa -107 million, Central Africa - 50 million, Southern Africa - 49 million, and Northern Africa - 13 million. To date, it is estimated that 768 million people, predominantly in developing countries, rely on substandard drinking water sources (WHO/UNICEF, 2013). Although the JMP believes that ‘‘improved’’ water should be available, not only for drinking, but also for food preparation, and for personal and home hygiene, there is no clear, official definition of how near a water source should be to a dwelling to be called improved (Hunter et al., 2010). Nevertheless, the United Nation has advocated a distance of 1,000 m as an appropriate distance for meeting the MDG targets (United Nation, 2003).

### 2.2.3 Challenges facing African Rural communities for access to safe drinking water

Internationally, the UN (2011) reported that from 1990 to 2008, 1.1 billion people residing in urban areas had gained access to an improved water source, and during the same period 723 million people living in rural areas also achieved the same goal. However, rural communities in African countries had the lowest access to clean and sustainable water supply compared to other developing countries in the world (United Nations, 2004). Access to safe drinking water supply continues to be one of the most complex challenges facing rural communities in Africa. Since 2000, the level of access to clean and safe drinking water in Africa has been reported to be only 47%, and about 320 million people still depend on access to unsafe drinking water in Sub-Saharan Africa.  Between 1990 and 2010, significant investments and initiatives were embarked on to improve access to safe drinking water, resulting in substantial improvements, with several countries achieving their Millennium Development Goal (MDG) target of halving, by 2015, the proportion of people without sustainable access to safe drinking water. In spite of these improvements, in rural communities of Africa, the proportion of people using unsafe drinking still remains a matter of great concern. Figure 2.2 illustrates the percentages of rural populaces within some African countries still using unimproved water sources. The largest rural population without access to improved water sources are found in Democratic Republic of Congo (72%), followed by Madagascar and Mozambique (71%), Angola (62%), Tanzania (55%), and Zambia (54%) (WHO/UNICEF, 2010).

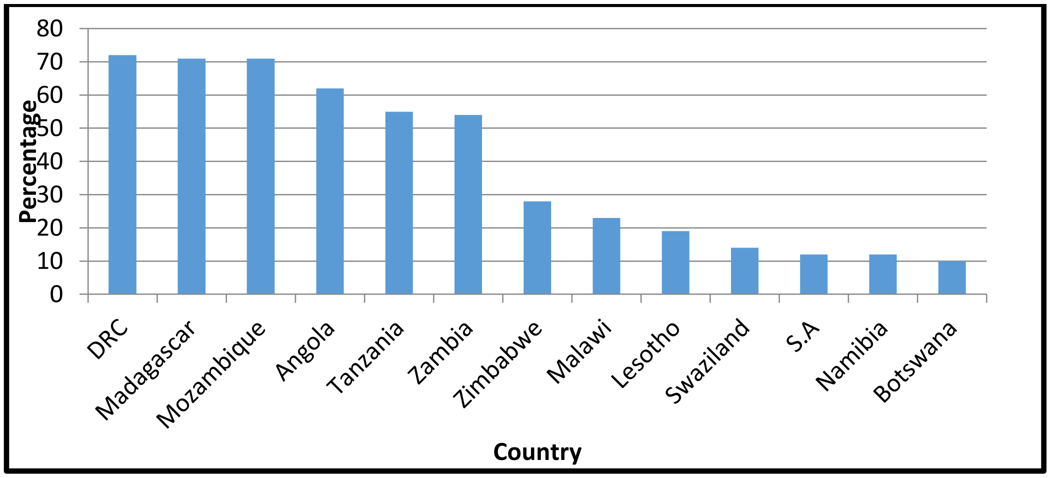


*Figure 2-3: Percentage of rural areas using unsafe water supply in the SADC region (Source - WHO/UNICEF JMP 2010)*

In general, inequality of access to advanced drinking water sources, are reported to be pronounced between rural and urban areas in sub-Saharan Africa, with the WHO/UNICEF JMP (2012) citing a 29% disparity in access to safe drinking water. It has been also reported that 97% of rural inhabitants do not have access to piped water in least developed countries (LDCs). Abitbol (2000) stated that 80% of health problems in Ethiopia, where 85% of the populace reside in rural areas, are attributable to poor sanitation and insufficient access to safe water. In Ghana, 64% of the populace resides in rural areas located mostly in the northern sector, of this rural northern population, 50% lack access to improved water sources (Kikkawa, 2008).

South Africa’s population stands at 49.4 million people, of whom 52% reside in rural areas. With its combination of developed and underdeveloped areas, South Africa contains approximately 3.5 million people who lack access to water supplies; an additional 5.4 million require that their access to drinking water be improved to meet minimum standard requirements (DWAF, 2008). The number of households in South Africa without access to piped drinking water is depicted in Appendix A. A large number of these communities rely on unsafe surface and ground water sources for their water related needs (DWAF, 2008). This is a matter of concern, considering that water is a primary necessity for all human beings.

### 2.2.4 Unsafe drinking water impact on public health and economic development

It is obvious that improved water service remains one of the greatest public health advances of the twentieth century; yet in the developing world, there is still evidence of disparity between rural areas and metropolitan areas in terms of access to safe drinking water sources. One reason safe drinking water is of paramount concern, is that 75 % of all diseases in developing countries are due to polluted drinking water (TWAS, 2002).The impact of deficient water and sanitation services in rural African communities is felt primarily on the poor. Women and children are the main victims as they are burdened by the need to carry water containers from long distances every day. Moreover, they endure the indignity, shame, and sickness that result from a lack of cleanliness.

Child deaths due to inadequate water and sanitation are a particular problem in Africa. In 2010, diarrhoea related diseases played a significant role in the deaths of children under the age of 5 years in countries such Angola (25%), Madagascar (22%), and the Democratic Republic of Congo (DRC) (19%) (WHO, 2010). In 2009, cholera outbreak cases in the SADC regions rose up to 60 055, 30 150 and 10 511 in Zimbabwe, DRC, and Angola, respectively (WHO, 2009). The assessment by the WHO revealed that 94% of diarrhoea cases can be reduced through interventions, such as increasing the accessibility of safe drinking water (Bartram and Gordon, 2008).

Majuru (2010) conducted a study that sought to determine the impact that community water interventions have on the rural populace of South Africa. The study was conducted over a 56 week period using three small rural communities situated in close proximity to each other in the Vhembe district of the Limpopo Province. At the beginning of the study, two of the communities collected water from a nearby river, but 17 weeks into the study both communities were provided with an advanced piped water supply by the local service provider. The remaining community was used as a control group, as they continued to use a river as its source of water for the entire study period. The results of the study showed reductions in diarrheal illness of about 57% in the first two communities. The marked reduction in illness provided important evidence of the value of small-community water supply interventions. An additional crucial observation of the study by Majuru (2010), was the reliability of the water supply interventions. A total of 21 weeks of system non-operation after the implementation of new water supply systems was observed. The author, therefore, recommended future studies on intervention projects that must be more robust, taking into account risk and maintainability of systems in all appropriate environments.

The lack of safe drinking water has also played a part in impeding the social and economic development of various developing nations, particularly those in Sub-Saharan Africa (Fogden, 2010). Economic development and access to safe drinking water equally depend on the same aspects, such as socio-economic stability (Fogden, 2010). Africa has experienced a large amount of socio-economic instability in the past half century. This has impeded government and potential investors from devising long term plans for the implementation and use of water treatment system infrastructure. It is widely recognized that the level of education of a country is one of the major determinants of economic growth (Fogden, 2010). A decrease in access to safe drinking water has an undesirable effect on education; this is because illnesses associated with drinking water, along with the time spent collecting water, can often preclude children from going to school. In a report by the United Nations (2006) it stated that in Tanzania, school attendance levels were found to be 12 % higher for school going girls who live less than 15 minutes from a water supply source than for those who live more than an hour away from a source. Further, children who go to school are believed to have a decreased learning potential because of parasitic infections derived from unsafe drinking water, which affects 150 million children throughout the world, each year

(United Nations, 2006). It is estimated that a lack of safe drinking water costs 443 million school days a year throughout the world (United Nations, 2006).

Advanced access to safe drinking water is likely to increase the rate of economic growth by improving the health and education of a population, and minimizing the costs of unsafe drinking water. There are several costs to the economy from drinking unsafe water, i.e. both direct and indirect costs (Fontaine et al, 2007). The direct costs relate to the heavy burden suffered by families for the treatment of diseases that come from drinking unsafe water. Many countries have a stationary rate of three episodes of diarrhea per year, meaning that a child could, on average, suffer from a water-related disease every four months (Fontaine et al, 2007). In a family of four or more children, there is a high possibility of a child carrying a fatal water-related disease at least once a month. At this rate even the most inexpensive of drugs become quite costly, and often unaffordable (Fontaine et al, 2007).

The indirect cost of bad health on the economy has two effects. The first is the loss of economic contribution of the sick (including those who have to care for them), and the prematurely deceased; the second, is the lower productivity resulting from sick workers (Fontaine et al, 2007). In sub-Saharan Africa, these two effects are further compounded by HIV/AIDS. Water-related diseases are of specific concern in countries with high numbers of people who suffer from HIV/AIDS, such as South Africa (UNICEF, 2005). A person suffering from HIV/AIDS, and consuming unsafe drinking water is likely to spend longer periods away from work due to the effects of water-related diseases on an already compromised-immune system. Kofi Annan proclaimed, at the start of the Decade for Action, where he spoke about the fight against HIV/AIDS that, “We shall not finally defeat the infectious diseases that plague the developing world until we have also won the battle for basic health care, sanitation and safe drinking water (United Nations, 2001).” As shown in Figure 2.3, an unsafe water source has the potential to cause human suffering, and it reduces the productivity of natural systems by imposing important economic and social costs on society. It impacts on individual productivity, which is greatly reduced by illness; families have a diminished disposable income due to the cost of medical treatment, and valuable time and energy is diverted in an effort to secure their water supply. The most susceptible situation is the death of thousands of people, especially children, occurring because of lack of clean and safe drinking water supply.

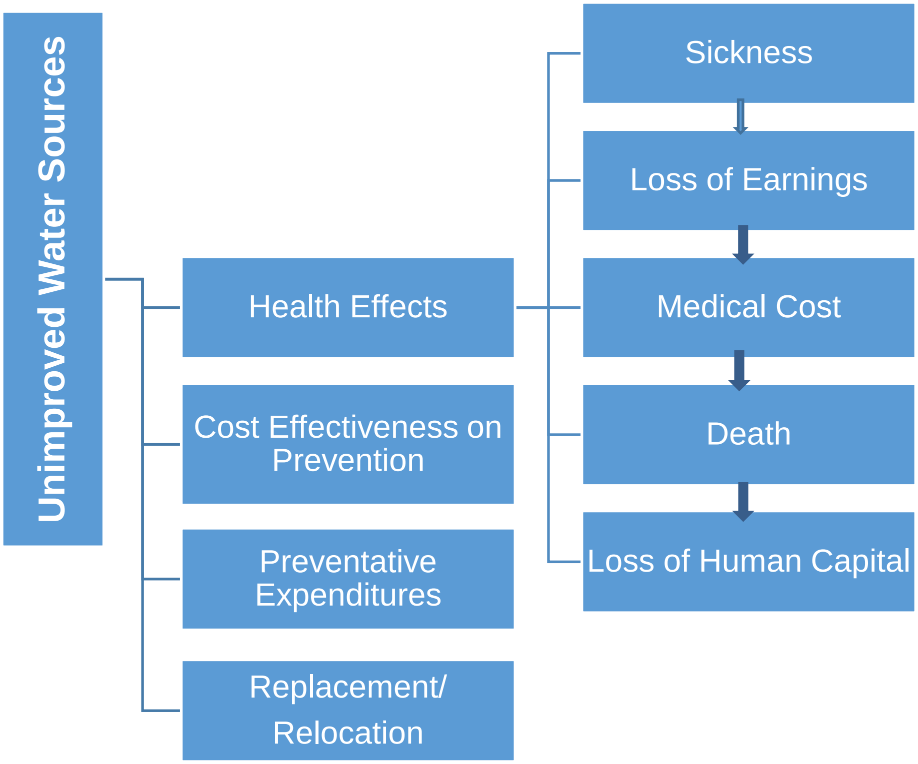


*Figure 2.3: Flow chart illustrating the burden of unimproved water sources in human life*

Collecting safe drinking water is a very time-consuming and laborious process. A study conducted by the Self Employed Women's Association (SEWA) in India, estimated that the mean time each household in India spends on water collection is 56 minutes a day (United Nations Development Programme, 2006). This is time that could be spent on conducting economic activity. Further, the same study found that decreasing water collection time by an hour per day could allow a woman to earn up to $100 more a year, depending on her initiative.

The gap between rural household inhabitants, and the timeous supply of safe drinking water, is an area of the Sub-Saharan social-economic complex that must be attended to in order to empower all Africans. Unsafe drinking water is a major hurdle to conquer in Africa, but its benefits will always outweigh the costs. Safe drinking water decreases child mortality, and also gives the adult population the opportunity to consistently be economically active members of the community. Within a rural setting, due to its sparse population, the number of economically active community members is even more important than in urban areas. It is crucial for African countries to promote the eradication of waterborne diseases in communities. Contaminated water has been reported to kill more people than cancer, AIDS, wars or accidents (TWAS, 2002).

Achieving the MDG target 7c, and eradicating waterborne diseases, requires not only the building of the drinking water infrastructure to provide services, but also taking actions to prevent current and future infrastructure from falling into disrepair as a result of inadequate institutional arrangements, insufficient cost-recovery, poor operation and maintenance, and an overall lack of sound management practices (WHO/UNICEF, 2006). Unless people have access to safe drinking water, efforts to prevent death from waterborne diarrhea, or to reduce the burden of such diseases as ascaris, dracunculiasis, hookworm, schistosomiasis, and trachoma, are doomed to failure. In light of this, there is an obvious need to assess, prioritize, and manage in a systematic manner the safety of water for the millions of people lacking access to improved basic services in African rural communities.  It is, therefore, essential to seek and implement technologies that respond to the needs and conditions of rural areas of Africa. In the next sections water quality standards, and the approaches that have been used to provide safe drinking water to the populace, shall be examined, while also identifying the gaps within these processes.

### 2.3 Safe drinking water technology options for rural areas in developing countries

It is extremely imperative that water, which is intended for human consumption, be free of disease-causing germs and toxic chemicals that pose a threat to public health. Given that more than 80 % of the world's population lives in developing countries (TWAS, 2002), technologies for making drinking water safe must be among the highest priorities, not only in urban areas, but also in peri-urban and rural areas. Appropriate, locally based strategies can, therefore, be devised to obtain safe drinking water in rural areas.

There are many factors to be considered for the design of appropriate water treatment systems. These include: cost, the concentration and type of biological and/or chemical contamination, concentration limits at which contaminant(s) are required to be removed, required flow rate, level of local expertise for on-going maintenance, and social acceptance. An ideal technology for rural areas should be effective at producing clean, potable water, however, it must also be at low-cost, low-energy demand (ideally energy-free), and require low-maintenance. Although, accessibility and affordability play an important role in the selection of the technology to be adopted, this technology must also be environmentally sound, and tailored to the community's cultural norms. Technology should supply the quantity of the water that is needed per person, per day in the dwelling. In South Africa, the basic level of domestic water supply is defined as 25 L per person per day, or no less than 6000 L per household per month (Department of Water Affairs, 2013). The following criteria are used for distribution (Department of Water Affairs, 2013): i) minimum flow rate of 10L per minute, ii) a standpipe within 200m of a household, iii) a maximum cumulative interruption time of 15 days, and iv) drinking water quality must comply to South African National Standards, SANS 241.

Technological options fall into two broad categories: centralized systems and decentralized systems. The first category is used by municipal authorities at centralized points from where water is then distributed. In Africa these technologies are mostly relevant in urban areas. The second category can be practiced in individual homes, especially in rural areas. This section discusses the advantages and disadvantages of these two categories of technologies, focus is largely placed on decentralized systems.

### 2.3.1 Centralized Drinking Water Supply Systems

#### *2.3.1.1 Overview of centralized systems: An option for urban areas*

The focus of the centralized water treatment systems is at the purification plant. This is the area where most value is added to the final product, which is safe drinking water (Department of Water Affairs, 2013). Centralized drinking water supply systems involve treated water pipe systems that deliver drinking water to all the communities in the geographical area served by the water treatment plant. This technology, therefore, requires an extensive pipe network, which should reach even the most remote communities (Swartz, 2009). Treatment processes involved in centralized systems are associated with high costs, and generally involve water source development, construction of infrastructure, and the adoption of a system to distribute the water to consumers

Optimization of centralized treatment systems plays an important role in the management of the waterworks. Problems related to the optimization of centralized water treatment plants can be categorized into two areas. The primary category involves the optimization of in-house operations. The second area of concern involves network location problems, where engineers use various modelling techniques to determine the optimal allocation of water supply resources, taking into account demand, resource availability, land terrain, and costs (Biehl and Inman, 2010). The modelling techniques can either be deterministic or stochastic in nature within a mathematical modelling or process simulation environment (Biehl and Inman, 2010).

In Africa, where a large proportion of the population resides in scattered rural communities, centralized systems are not economically feasible, therefore, alternate methods of providing potable water to these communities should be considered. The following sections discuss decentralized drinking water treatment systems and the methods to efficiently deploy them in rural areas.

## 2.3.2 Decentralized Drinking Water Supply Systems

Decentralized systems have been identified as short to medium term sustainable solutions for the provision of safe drinking water to rural communities, to reduce or even eradicate, waterborne and water-related diseases (Swartz, 2009). To achieve this goal, the technology should not only be able to improve the taste and appearance of drinking water, but to substantially improve the microbiological quality of water. Effective methods at the family and community level, can bring a rich supply of substantially clean water with little effort and at a reasonable cost. In other words, any decentralized water purification system must satisfy the specifications that point toward the safety of drinking water. These specifications offer a benchmark for manufacturers to determine the acceptability level of the treated water they produce for human consumption. In South Africa treated water must comply with the SANS 241. Many parts of the world use the World Health Organization criteria as a water quality standard (WHO, 2002).

### *2.3.2.1 Household drinking water technologies*

The expense associated with centralized water treatment has led to an increase in approaches for the design and use of decentralized household drinking water treatment technologies. Household drinking water treatment systems are practical and desired in both the developed and developing world. There are numerous household water purification systems available in the market, each containing its own specific manufacturing process. A high level of consideration must be placed on the manufacturing processes for each treatment system, because this has a direct impact on the final cost of the product. Further, the cost of deploying the product to those who need it most, including procurement and material distribution costs, must also be kept to a minimum level. As this product is intended for use by those in rural communities who cannot directly afford it, costs play an integral part in the final consideration of a product’s viability. Many countries have devised successful practices based on household decentralised systems. Figure 2.4 illustrates the locations of studies conducted in household drinking water treatment, as well as storage interventions in developing countries.

*Figure 2.4 Locations of Studies of Household Drinking Water Treatment/Storage Interventions in Developing countries (Source: Wright et al., 2004)*

Household drinking water treatment methods can be broadly divided into three categories (Sobsey, 2002; (Momba et al., 2014) : i) methods which involve the physical removal of microbes and other particles, ii) methods which result in their destruction or deactivation (disinfection), and iii) methods which are able to remove chemical contaminants. Among point-of-use (POU) drinking water technologies, the following have been used in many developing countries, and have demonstrated to markedly improve the microbiological quality of water: filtration, chlorination with storage in an improved vessel, solar disinfection in clear bottles by the combined action of UV radiation and heat, thermal disinfection (pasteurization) in opaque vessels heated in solar cookers, and combination systems employing chemical coagulation-flocculation, sedimentation, filtration and chlorination (Sobsey, 2002). For the purpose of this study, the scope is limited only to household filtration systems, as these systems have been extensively studied in South Africa, and proved to be cost-effective, easy to be manufactured and operated by the rural communities. Moreover, materials used in their design are locally accessible and available, as well as robust.

#### *2.3.2.1.1 Household sand filters*

**a) Biosand filter (BSF)**

The biosand filter was developed by Dr David Manz of the University of Calgary in Canada. It is an adaptation of the traditional slow sand filter. The most common biosand filter is constructed with concrete and has five distinct zones: the inlet reservoir zone, the standing water zone, the biological zone, the non-biological zone, and the gravel zone (CAWST Training Manual, 2009). The vessel is generally filled with sand filter media and gravel, with elevated piping that allows the filter to maintain a five centimeter layer of water above the sand surface to prevent it from drying out. The generic size dimensions of biosand filters consist of a height of 90 cm and a width of 30 cm, with the fine sand media layer being 40–50 cm high (CAWST Training Manual, 2009). Figure 2.5 illustrates the generic BSF made with concrete materials, and the drawing of the internal dimensions of the BSF is shown in Figure 2.6.

To adapt the BSF filter to rural South African conditions, a project was commissioned by the Water Research Commission (Project K5/1884/3), and the filter was modified by Momba and co-workers (2014). The first modification made to the design of the BSF was the use of a 25 ℓ plastic bucket (height 41 cm and width 32 cm), and the filter media at a height of 15 centimeters. The removal of pathogens and suspended solids is done through a combination of biological and physical processes (Momba et al., 2014). The development of a biological, active layer at the top of the filter bed, improves the removal of contaminants. Contaminated water is poured through a reservoir on a sporadic basis (Momba et al., 2014). The water slowly passes through the biolayer, sand and gravel, and the treated water flows through to the outlet tube. The drop in water flow is a warning that indicates the clogging up of the filter. To increase the flow, the filter should be cleaned by agitating the top few centimetres of the filter media, and scooping up the dirty water released (Momba et al., 2014). According to these authors, the size of the filter was scaled down to ensure that the filter would not take up too much space in a small rural home. As mentioned above, the biosand filters are quite simple to construct, and almost anyone can be trained to produce the filters if the appropriate materials are provided. Figure 2.7 illustrates the modified BSF that was manufactured based on the South African conditions.

*Figure 2.5: The Biosand Filter made with concrete materials (Source: Earwalker, 2006)*

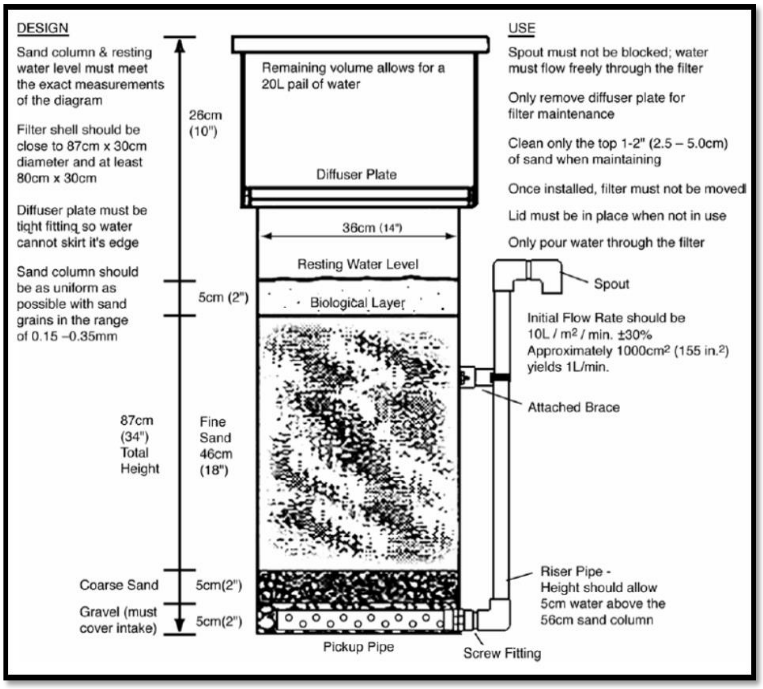


*Figure 2.6: Drawing of the Internal Dimensions of the BSF*

*(Samaritans Purse, 2003)*

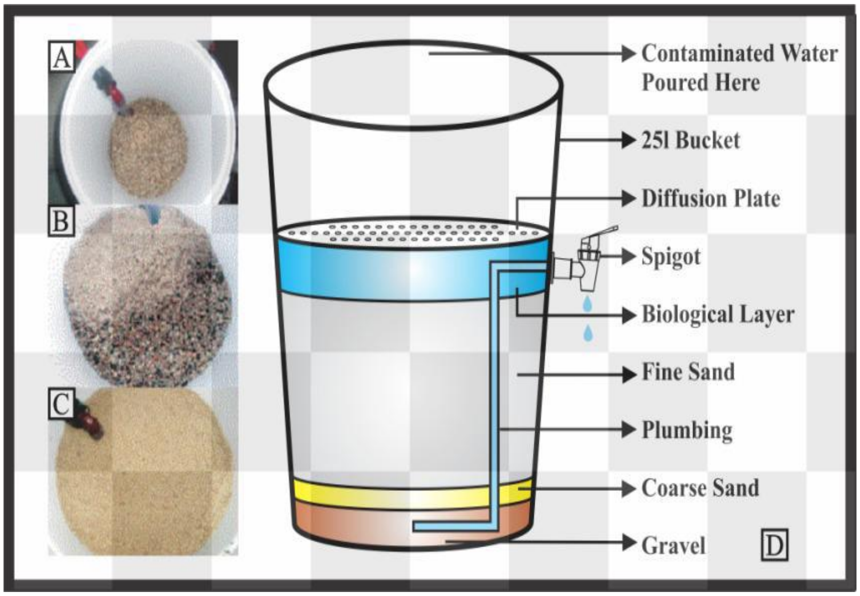
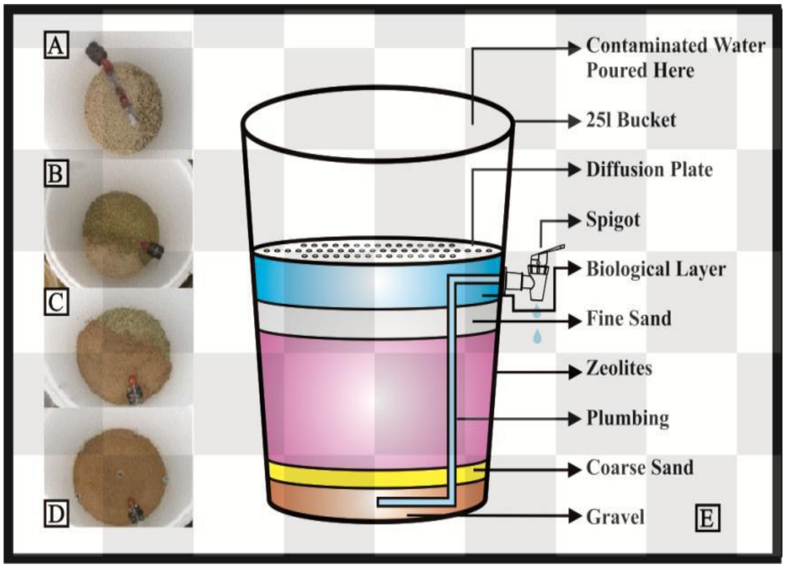


*Figure 2.7 Drawing design and components of different layers of a BSF unit: A – Gravel Layer (2.5 cm), B – Coarse sand layer (1 cm) together with the gravel layer, C – Fine sand layer (15 cm), D – Skeletal view of a BSF-S showing the internal content. The modified BSF was developed by Tshwane University of Technology (Source: Momba et al., 2014).*

### b) Biological Sand Filter with Added Zeolites (BSF-Z)

The BSF-Z was also developed and tested by Tshwane University of Technology. It is an adaptation of the standard BSF filter. With an exception of a 10 cm layer of zeolites included in its filter bed, the layout construction of BSF-Z is similar to that of the standard biosand filter. This was the second modification made by the investigators concerning the biosand filter (Momba et al., 2014).

Zeolites are hydrated aluminosilicates composed of symmetrically stacked alumina and silica tetrahedral. This gives it an open and static three dimensional honey comb structure, with a general negative charge that is neutralised by exchangeable cations, such as sodium (Mahlangu et al., 2011). Zeolites have both ion exchange and molecular sieve properties. The advantages of zeolites for use in water treatment, comprise the simplicity of its modification to remove certain chemical contaminants, their abundance in nature, low costs and their regenerative properties (Widiastuti et al., 2008). Clinoptilolite is the most abundant natural zeolite, and it is widely used in water and wastewater treatment (Mahlangu et al., 2011). The removal of metals, such as Iron, Manganese, Zinc, and Copper from acid mine drainage by natural zeolites, has been reported (Motsi et al., 2009). Zeolite has also been used in water treatment systems for the removal of ammonium, heavy metal ions, and inorganic anions (Mahlangu, 2010). A number of investigators have reported the removal of phosphates and ammonium from water and wastewater by zeolites synthesised from coal fly ash (Nunez, 1998; Wu et al., 2006, 2008; Zhang et al., 2007). Figure 2.8 illustrates the components of the BSF-Z developed by Momba and co-workers (2014).



*Figures 2.8 Drawing design and components of the four layers a BSF-Z unit: A – Plumbing, gravel and coarse sand layers, B – Coarse sand layer and zeolite layer, C – Zeolite layer and fine sand layer, D – Fine sand layer with supports for the diffusion plate, E – Skeletal view of the BSFZ showing the internal content (Source: Momba et al., 2014)*

### c) Bucket Filter (BF)

A bucket filter is a sand filter which is mainly constructed with two buckets, commonly plastic, with a capacity of 10 ℓ to 40 ℓ. The BF device constructed by Momba and co-workers (2014) had a capacity of 25 ℓ. The two buckets of similar size are stacked on top of each other to constitute a filter. The bottom of the top filter bucket is perforated, and the filtered water drips into a second bucket, on top of which the filter bucket is placed. The filter media comprise a 20 cm layer of fine sand (0.3 mm), and a five centimeters layer of gravel (5 mm), which are packed into the top bucket. Bucket filters are frequently used for the pre-treatment of turbid water prior to disinfection. Generally, the filter media has to be periodically removed from the bucket and cleaned or replaced (typically after several weeks) (Momba et al., 2014). Figure 2.9 illustrates the BF device.

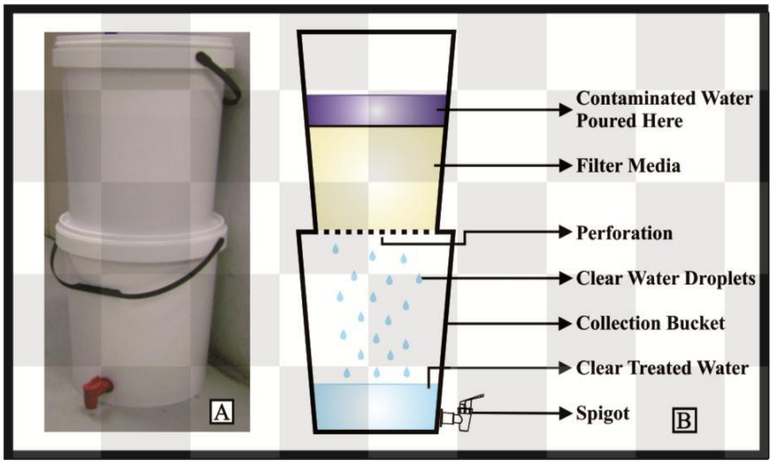


*Figure 2.9 The plastic BF devise with a capacity of 25 L (A) and the drawing design showing the components of  the unit (B) (Source: Momba et l., 2014)*

### *2.3.2.1.2 Clay pot filters*

**a) Potters for Peace Filtron (PFP)**

The Potters for Peace Filtron (Figure 2.10) is a popular filtration system developed by the Potters for Peace non-profit organization (Dies, 2001). The system consists of a colloidal silver-impregnated ceramic pot that is suspended inside a collection bucket. The filter unit has a capacity range between 7.5L and 20L (Dies, 2001). Water is poured in at the top of the filter, and filtered through the ceramic pot.

*Figure 2.10: PFP filter System (Source: www.potpaz.org)Silver Impregnated Porous Pot (SIPP)*

The silver impregnated porous pot SIPP is a prototype nanotechnology-based clay pot filter designed by Tshwane University Water Research Group (Momba et al., 2010), and manufactured by the CermaLab Testing Laboratory, Pretoria/South Africa. A combination of sawdust, ball clay, paper fiber, and silver nitrate solution is moulded into a pot shape and then fired at 950 degrees Celsius. The silver nitrate acts as a disinfectant due to the bacteriostatic properties of the nano-silver particles (Momba, 2010). Figure 2.11 depicts the SIPP device. This treatment system consists of the pot filter with a capacity of five litres that is held within a ten litres plastic receptacle.

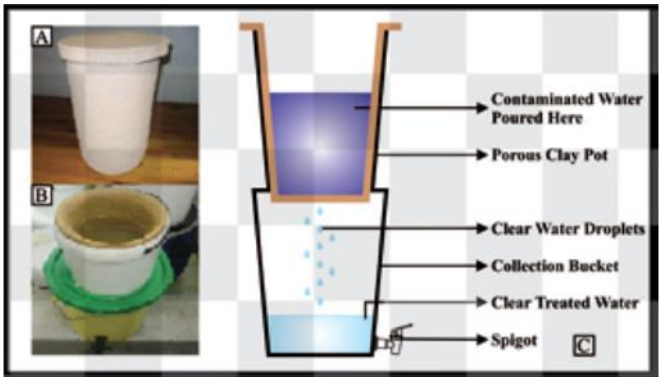


*Figure 2.11: The Silver Impregnated Porous Pot*

*(Source: Momba, 2010)*

The plastic receptacle is placed on top of a 20 L collection bucket. Unclean water is poured into the clay pot, the water then gradually drips through the fine pores of the clay element into the collection vessel. A small spigot is used to extract safe drinking water from the collection bucket (Momba, 2010).

#### *2.3.2.1.3 Ceramic Candle Filters*

The ceramic candle filters consist of an upper and a lower container similar to the SIPP (Momba et al, 2013). The ceramic candle is positioned in the top container where the unclean water is received. Typically the containers have a diameter of about 30cm by 25 cm depth, which allows for a treatment capacity of about eight litres, and a flow rate of one to two litres per hour, per candle. The ceramic candles are screwed into the base of the upper container. Purification of the water occurs through mechanical trapping and adsorption in micro-scale pores of ceramic candles. Colloidal silver is sometimes added to the candle in order to increase the efficiency and effectiveness of pathogen removal.

Water is poured into the upper container, and flows through the candle, collecting in lower container. A tap is attached to the lower container, which allows the withdrawal of safe water without risking recontamination. A lid is placed on top of the upper container to prevent contamination. The candle filter along with the ceramic candle filtration element is depicted in Figure 2.12.

*Figure 2.12: Candle filter with ceramic candle filter element (Source: Harvey et al, 2009)*

### *2.3.2.1.4 Performance of household drinking water technologies*

Low cost household water purification units have been reported to be effective in removing pathogens causing waterborne diseases (Sobsey, 2002; Murcott, 2006; Momba et al, 2013). Prior to the selection of a particular household drinking water technology, it is imperative to take into consideration its performance in producing drinking water that complies with the required standards in terms of quality and quantity. The life span of the system should also be considered. Table 2.3 summarises the performance of the abovementioned household drinking water treatment systems based on the studies conducted in South Africa by Momba et al. (2010, 2013, 2014), Mwabi et al. (2011, 2012), and Adeyemo et al. (2014).Table 2.3: Microbial removal performance of selected household Drinking water treatment systems.

These units are easy to construct, and input materials are readily available at low costs. The lack of water treatment facilities in rural areas makes household purification units, as well as small scaled piped systems, a feasible alternative. Though there is a lot of literature on household water purification systems, there is a dearth in strategies used to evaluate and select the appropriate units to those who require it most. Decision support systems models, such as Multi Criteria Decision Making (MCDM) models, can help by bringing together expert opinions in the water treatment, and all associated fields to determine the most optimal water treatment system in a particular rural area. These deployment strategies are discussed in section 2.4.

*Table* ***Error! No text of specified style in document.****-3: Performance Household Drinking Water*

| **HWTS** | **Microbial removal (%)** | | | **Turbidity Removal (%)** | **Water production (L/ day)** | **Comments** |
|---|---|---|---|---|---|---|
| | Bacteria | Viruses | Protozoan parasites | | | |
| BSF | 60-100 | 73.2-96.3 | 92-96 | 32-98 | >100 | The BSF has been proved to effectively remove bacteria and protozoan removal, though virus removal is poor. |
| BSF-Z | 90-100 | 80.5-100 | 92-95.75 | 12-97 | >150 | The BSFZ has higher flow if 3 mm zeolites used, though the Zeolite layer may need to be replaced periodically. |
| BF | 40-99.9 | 82.1-96.3 | 88.87- 95.55 | 30-95 | >150 | The BF reduces disinfectant demand while improving disinfection efficiency. There is a limit of performance data for the BF. |
| PFP | 100 | 90.6-100 | 96-99.15 | 30–100 | 10-20 | The PFP has been proven to be effective against bacteria and protozoa, it is also simple to use. It needs to be regularly cleaned. |
| SIPP | 100 | 90.6-100 | 96-99.15 | 59- 99 | 10-20 | The SIPP has a long filter life if it remains unbroken. The filter has low flow rates (1-4 ℓ /h) even for low turbidity waters |
| CCF | 90-100 | 77.1-100 | 91.72-97.97 | 40-98 | 20-40 | The filter elements of the CCF are compact and easy to transport. |
| *Estimated life span for all these household drinking water treatment system has been reported to be three years (Momba et al., 2013)* | | | | | | |

### *2.3.2.2 Access to improved groundwater sources*

One of the major strategies for tackling the problem of access to improved drinking water sources in African rural communities, is the installation of protected sources, such as boreholes, standpipes, or wells to provide water of better quality. Compared to groundwater sources, surface water sources are often highly polluted, and the infrastructure to pipe water from fresh, clean sources to arid areas is very costly. Consequently, groundwater remains the best resource to supply clean water to the majority of areas in Africa, especially in rural areas. In addition, groundwater has the benefit of being naturally protected from bacterial contamination, and is a reliable source during droughts (Howard et al., 2006). However, the main challenge facing the communities is the high costs associated with drilling for water, and the technical challenges in finding sources that are large enough to serve the population in need. There may be also contamination of the water with heavy metals, and bacteria may be introduced by leaking septic systems or contaminated wells. For these reasons, there is a need for groundwater to be monitored frequently, a process that is costly and requires technical abilities that may not exist in rural areas (Awuah et al., 2009).

Although overall groundwater drilling costs may be high, groundwater still shows significant advantages over surface water. It may be conveniently available close to where it is needed. It can be developed at a relatively lower cost and in stages to keep in stride with increasing demand. Overall the capital costs related with groundwater development is usually less than with large-scale surface water supplies. Additionally, aquifers are often well protected by layers of soil and sediment, which essentially filter rainwater as it permeates though them. Therefore, the removal of particles, pathogenic microorganisms, and many chemical constituents from groundwater sources occurs naturally. It is generally assumed that groundwater is a relatively safe drinking-water source (Howard et al., 2006).

Groundwater has been labelled the ‘hidden sea’ because of the vast amounts of water hidden underground. This contributes to the notion that pollution pathways and processes of groundwater systems are not always detailed (Chapelle, 1997). Attention is needed to establish whether the general assumption of groundwater being safe to drink, is valid in discrete settings. Understanding the source-pathway-receptor relationship in any particular setting, where groundwater is used, is critical to ascertain whether pollution will occur (Chapelle, 1997). Whilst there is vast amount of water in this ‘hidden sea’, its replenishment occurs sluggishly at rates varying between localities (Chapelle, 1997). Excessive groundwater abstraction in relation to replenishment leads to depletion of the source, and increases competition between users. Heavy-duty hydraulic gradients, resulting from abstraction, can cause the development of preferential flow paths for the groundwater. This reduces the efficiency of the natural treatment processes leading to increased concentrations of contaminants in groundwater. Moreover, changes in groundwater levels, induced by abstraction, may alter settings above the surface significantly. For example, redox conditions may change, and thus cause the mobilization of natural or anthropogenic contaminants (Chapelle, 1997).

Some groundwater sources contain constituents that are of concern to human health, particularly fluoride and arsenic. Nevertheless, understanding the influence of groundwater on public health is often difficult as many communities that utilise groundwater are small (Chapelle, 1997). Therefore, outbreaks of disease are unlikely to be detected, especially in countries with inadequate health surveillance. Additionally, it is frequently impossible to recognize the cause of an outbreak as many risk influences are involved (Chapelle, 1997). Further, water that is of good quality at its source, may be re-contaminated during extraction, transport, or household storage. This may require subsequent treatment and safe storage of water in the home (Sobsey, 2002).

The natural quality of groundwater makes its use valuable in industry, and it may provide environmental benefits through renewal of rivers and streams, or for the growth of agricultural vegetation (Sobsey, 2002). Therefore, these benefits support the need for its protection. Protecting and conserving groundwater will create costs to society through production costs caused by pollution control and treatment requirements. When developing protection plans and policies, the cost of implementing such measures must be taken into consideration, as well as the cost of not protecting groundwater. A competent cost benefit analysis allows for balanced decisions to be made. Being an important source of drinking water for rural African areas, the extraction and costing of groundwater sources for drinking purposes in rural areas, forms a major part of this study. In South Africa, some rural communities receive underground water from a borehole using a rotary hand pump which is connected to a standpipe, while others obtain their drinking water directly from standpipes, which are connected to the boreholes.

Stand pipe systems are small scaled piped systems supplying water via communal taps or yard taps (Momba et al., 2013). This makes them economically feasible for rural areas. Stand pipe systems, being on such a small scale, often rely on community management for effective operations. Small piped water systems are often fed by gravity from protected springs, surface water, or borehole systems equipped with motorized pumps. Most piped systems are equipped with storage tanks, such that water is constantly available. The location of taps must be considered carefully when planning a piped system; this must be done in order to maximize accessibility. Piped systems require regular maintenance, leaks must be repaired in order to prevent the loss of water, and to prevent surface water from entering the pipes and contaminating the water supply.

The research into the development water treatment systems for use in rural areas is well advanced. There are numerous water purification systems available that can be used to help alleviate water problems in rural areas. The water treatment systems presented are not agnostic to the socio-cultural and economic context of particular areas. The problem lies in selecting the appropriate water treatment system given a particular rural context. The industrial engineering field can solve this problem by providing decision makers a scientific solution geared towards selecting an appropriate water treatment system. The following section identifies some of the tools available for the development of a water treatment system selection model.

### 2.4.4 Supply Chain Design

Supply chain design and planning is vital to the success of deploying purification systems to rural, scattered African villages. Detailing the end to end supply chain processes of a water treatment system can allow one to begin to closely analyse activities and processes against specific criteria. In this section, we analyse the mechanics of supply chain design and management. We also look at analytical decision making tools that may provide assistance in selecting the ideal water treatment system.

Supply chain Management has to do with smooth, economically driven operations, and maximizing value for the end user through quality delivery (Al – Mudimigh et al., 2004). Managing a supply chain effectively, improves competitiveness by reducing uncertainty, and enhancing customer service. Supply chain design and management has evolved over the last few decades. In the 1960's, supply chains were usually focused on functions, and optimization was conducted within functional silos with little to no regard to the external inputs that may have had an influence on functions. The relationship with companies and vendors was usually based on win-lose interactions, and most manufacturing systems were focused on material requirements planning (MRP) (Turbide, 1997).The 1970's brought with it the recognition that a number of functions within a firm would benefit from integration, such as manufacturing and product design. At the same time various quality initiatives, such as total quality management (TQM) and ISO standards, were designed according to the philosophies of Deming and Juran, among others (Turbide, 1997). Due to the increase in global competition from the 1990's onwards, companies started forming strategic alliances in order to lower costs and increase efficiency. Numerous organisations started analysing the total cost for a product from source to consumption (Turbide, 1997). Information technology tools, such as enterprise resource planning, electronic commerce, and collaborative engineering became more prevalent.

In a few short decades, supply chain design went from focusing on function, to becoming more process, and system oriented. The process decomposition of a supply chain helps to analyse criteria such as the costing, maintainability, sustainability, risk and the accessibility of certain products and services as they relate to particular environments. This decomposition helps to determine how a water treatment system will perform against such criteria, which facilitates the evaluation and selection process.

Costing plays a vital role in the design and management of a supply chain, even more so when seeking to deploy products to rural areas. Accurately estimating the cost of operations has become an intrinsic strategic goal for the success of engineering projects and businesses. In response, there has been an increase in literature concerning cost estimation and management in both product design and supply chain operations. Furthermore, the decomposition of a supply chain helps to cost the end to end processes involved sourcing, manufacturing and deployment of products and services.

Cost estimation methodologies are categorized into four sections: intuitive, analogical, parametric, and analytical methods (Ben-Arieh, 2003). Intuitive methods involve estimating costs based on past experiences and personal knowledge. Analogical methods evaluate product costs based on comparison with similar parts. Parametric methods estimate costs based on critical parameters of a product which effect costs in a known way. This method is usually represented by a simple equation. Analytical methods estimate the costs of a product by breaking down the work conducted into fundamental tasks and activities. Each activity cost, both direct and indirect, is calculated, and then summed to achieve the final cost (Ben-Arieh, 2003). When designing a supply chain intended for the deployment of water purification systems in rural areas, analogical costing methods may be one to consider. This is because most products and activities involved in the supply chain are readily available and well known. Therefore, comparisons of product parts, manufacturing activities, sourcing activities, and distribution activities can be easily made.

One of the more popular analytical methods that is currently being applied, is called activity based costing (ABC). This method involves tracing the cost of activities in the production and service industry. ABC leads to more accurate and traceable cost information, and classifies activities as value adding or non-value adding activities (Gunasekaran and Sahardi, 1998). Analytical methods, such as ABC, promote the integration of process modelling with cost estimation. A quantitative analysis of cost, using ABC or another analytical method, is conducted after process model structure is visualized. Katja et al. (2002) presented an analysis of the potential that ABC and process modelling can have as a tool for the evaluation of different design options within a manufacturing environment. This study looked at the relationship between activities performed in an organisation and their associated costs. The study concluded that the integration of ABC and process modelling provided a good initial point for heading toward a more cost conscious design, and provides an effective tool for the evaluation of different design options (Katja et al., 2002). Integrating process modelling in the form of value chain mapping, together with ABC, could possibly provide an accurate visual representation of a supply chain with the focus on low costs, risk, sustainability, and a positive social impact.

The decomposition of supply chain into sequential activities helps to analyse and quantify criteria such as cost, risk, accessibility of certain products and services. Furthermore, it facilities the comparison of the supply chains of products and services and the results of this comparison can be used in selecting the appropriate product given a certain environmental context. The following section looks at the tools used to select a product or service based on a set of criteria

### 2.4.5 Decision Making Tools: Multi Criteria Decision Making (MCDM) Models

The MCDM approaches form significant parts of decision theory and analysis. They are valuable in situations which require the deliberation of diverse courses of actions which cannot be evaluated by the measurement of a single, simple dimension (Al Harbi, 2001). MCDM models are used as decision aids in the evaluation of a set of alternative options or strategies based on a predetermined set of criteria. The comparison of various alternatives is based on their values for each criterion (Sarkis, 2000). In most methodologies, the multi criteria evaluation for an alternative $a$ is characterised by the vector $g(a) = (g_1(a), g_2(a), g_3(a),\ldots,g_m(a))$, where $g_j(a_i)$ is the performance of the alternative $a \varepsilon A$ with regard to the criterion $g_j$ . This information is then used to determine relative rankings of each alternative for a given criteria. Preference weights and thresholds for each criterion are predetermined by the relevant decision makers (Sarkis, 2000).

There are a number of MCDM tools available to help stakeholders to make valid and rational decisions. This helps to make the decision process transparent and traceable. Some popular MCDM tools include Mathematical Programming (LP), Data Envelopment Analysis (DEA), Analytical Hierarchy Process (AHP), Case Based Reasoning, Analytic Network Process (ANP), Fuzzy set Theory, Simple Multi Attribute Rating Technique (SMART), and Genetic Algorithms (GA) (Ho et al., 2009). There are also integrated MCDM decision making tools. Tools such as integrated AHP and DEA, integrated Fuzzy and multi objective programming, and integrated AHP, DEA, and artificial neural networks can be used as decision support systems (Ho et al., 2009). DEA, AHP and mathematical programming are the most commonly used approaches, especially in the field of supply chain design, with a focus on supplier selection (Ho et al., 2009). One of the advantages of MCDM tools, is that they afford techniques that are adept at improving the transparency, audibility, and analytic rigour of decision making (Hajkowics and Collins, 2007). MCDM is useful in water resource management because deployment of resources in this sector is often guided by multiple objectives. Further, MCDM affords a ‘paper trail’ and accountability to decision making processes, which may otherwise have indistinguishable motivations. Transparency in MCDM decision making procedures is realized by unambiguously declaring and weighting decision criteria, and then stating reasons for choosing such criteria. This allows for past decisions to be easily audited (Hajkowics and Collins, 2007).

Hajkowics and Collins (2007) identified eight MCDM applications used in water resource management. They include catchment management, ground water management, infrastructure selection, project appraisal, water allocation, water policy and supply planning, water quality management, and marine protected area management. Catchment management concerns land use and land management patterns. Within the ground water management sphere, MCDM is typically used for choosing actions for remediation of contaminated ground water supplies. Infrastructure selection involves the selection of appropriate water related infrastructure for a city or region. Projects are appraised by ranking a set of waste water management projects. Water allocation applications use MCDM to derive decisions concerning how much of a limited resource to allocate for competing uses. Water policy determination used MCDM to evaluate policy options, such as levies, legislation, as well as long term strategic planning for a region's water supply. Water quality management practices apply MCDM to assess options designed to specifically improve water quality. Marine protected area management uses MCDM to manage near shore marine environments. The bulk of the studies used a wide range of economic, environmental, and social criteria. The most frequently used criteria included cost of options, along with calculations of net present value, and economic impacts, such as potential for job creation, technical feasibility, water quality and supply, and distribution benefits, which included fairness and equity concerns.

### *2.4.5.1 Analytical Hierarchy Process (AHP)*

AHP is a decision support methodology within the MCDM field that was developed by Saaty (1980). Its objective is to quantify the relative priorities for a given set of alternatives on a ratio scale based on a set of criteria that is determined by a group of expert decision makers. Group members use their knowledge and experience to disseminate a particular problem into a hierarchy, and proceed to solving it using the AHP steps. The group decision making function of AHP allows for brainstorming, and the sharing of ideas and insights, this leads to a more thorough understanding of a problem, which in turn leads to a more complete final decision. Each criterion is given a weight that is based on its relative importance.  A summary of AHP processes is as follows:

1. Define the problem, its goals, and the relevant decision criteria,
2. Identify a group of relevant decision makers to partake in the AHP decision making process,

3. Structure a hierarchy from the top which contains the objectives, from the intermediate levels containing the criteria, through to the lowest levels which contain a list of alternatives
4. Compare each alternative which each criteria by developing a comparison scale along with a priority matrix, priority matrix and consistency ratio, and
5. Determine the best overall alternative.

AHP was used by Al-Harbi (1998) within the project management sphere to identify preferred contractors based on certain pre-qualification criteria. Pre-qualification is the screening of potential construction contractors by project managers in order to determine their suitability to partake in a project bid. Criteria such as experience, financial stability, quality performance, manpower resources, equipment resources, and current work load were taken into account in order to determine a suitable candidate. Aitah (1988) studied a bid awarding system for building construction projects in Saudi Arabia. The author concluded that projects awarded to the lowest bidder were subject to lower performance quality and delays, than those awarded based on specific prequalification criteria. This is one of the main advantages of AHP because it brings a high level of rationality to decision making in industry. Lai et al. (2002) used AHP within a group decision setting to determine which Multimedia Authorizing System (MAS) to use for a software development company.

A noteworthy amount of literature concerning MCDM is devoted to the use of AHP and integrated AHP methods in the supply chain design sector. AHP is principally used in the selection of supply chain partners and network location problems. The selection of supply chain partners are based on several criteria, such as costs, quality, service, and organisation. Korpela et al. (2001) used AHP to analyse the potential projects of a logistics environment within a group setting. Chan (2003) applied AHP processes to produce an overall score for alternative suppliers based on costs, quality, and design criteria. Muralidharan et al. (2002) suggested an AHP process using a cross-functional team of experts from the same company to identify and select appropriate suppliers.

Tahriri et al. (2008) used AHP within a manufacturing environment to select the most appropriate suppliers using 13 different criteria.

Integrated AHP models have been used by researchers to model complex problems in industry. Korpela et al. (2001) sought to optimize a company's supply chain by incorporating customer preferences using an integrated AHP and mixed integer programming (MIP) model. The model incorporated customer satisfaction by using AHP to determine the strategic importance of each customer segment, using profitability, partnership, sales volume, and financial viability as criteria. Further, AHP was used again to determine each customer segment's preference for service elements, using risk of delivering time, risk of the condition of products, flexibility of urgent deliveries, flexibility of capacity, cost level, and value added services as criteria. The final phase of the study involved optimizing the supply chain to accommodate the customer priorities determined by the AHP. The objective function maximized the customers' priorities subject to the physical constraints of the supply chain network. Ghosypour and O'Brien (1998) presented a model where AHP was used to calculate a numerical rating of company suppliers. The ratings were then used as coefficients of a linear program objective function that allocated order qualities between various suppliers in order to maximize the total value of purchasing. Integrated models, using AHP and linear programming, have added value in multi-criteria decision making problems by using the ability of AHP to model qualitative factors, and supplementing this with linear programming's ability to accurately handle quantifiable factors. The use of this technique has widened the breadth of problems that can be modelled, and has also brought about more accurate results.

Tahriri (2008) argued that the selection of decision criteria, along with identifying the appropriate group of decision makers to participate in the AHP process, are the most important functions prior to the starting the process. These two functions contribute to the accuracy of the final decision. Within the AHP process, giving the appropriate relative weight of each criterion will also increase the accuracy in the final decision. The appropriate weighting of each criterion is a function of the knowledge of the decision makers, because it is them that will give the criteria its relative weight.

AHP was applied by Kurka (2013) to evaluate the regional sustainability of bioenergy generation in a case study of Tayside and Fife, Scotland. The study took account of two different scenarios, each containing two alternatives. In each scenario there was a choice of either a large scale single centralized bioenergy generation plant, or multiple medium scale decentralized bio- energy generation plants. The final decision was based on four criteria: environmental, technical, economic, and social. Bioenergy specialists from diverse forums partook in the AHP process. The final decision concluded that decentralized alternatives were favoured in both scenarios. This study provides a good example for the evaluation and selection of different deployment strategies for different household water purification systems. In the deployment strategy, there were two different scenarios each containing three different deployment strategies. AHP was used to identify the most appropriate deployment strategy.

Derivatives of AHP such as multiplicative and additive AHP are thought to overcome some of the perceived failures of AHP (Lootsma, 1997). Multiplicative AHP was thought to better mimic the thinking process of human beings using a geometric grading scale as opposed to the linear scale presented by AHP. Additive AHP is the logarithmic equivalent of multiplicative AHP, which makes it easier to manipulate mathematically (Lootsma, 1997). The failures of AHP are further discussed by Lootsma (1997).

AHP and its derivatives can be used in any industrial project where there are a set number of criteria and alternative options; it is instrumental in situations where the final decision has wide ranging ramifications. Therefore, it is viable to extend the use of AHP to sectors such as rural development and, specifically, the selection of the appropriate water treatment systems to be deployed in Makwane village. The application of AHP could be fruitful in providing the best path for the selection of appropriate water purification systems. Further, the fact that AHP takes into account both tangible and intangible criteria, makes it ideal to handle qualitative criteria, such as the social impact criteria

### *2.4.5.2 Goal Programming*

Goal programming is an extension of linear programming, and is the most widely used MCDM approach (Romero, 1991). Goal Programming is a MCDM linear programming technique used to model conflicting objectives. It was initially developed by Charnes and Cooper (1961), and further developed by Tamiz et al. (1998) and Romero (1991). In numerous real world cases, decision makers face multiple objectives (goals), some of which may be conflicting, and may seek to achieve these goals, or get as close to these goals as possible, given constrained resources within an organization. Goal programming provides the mathematical modelling platform for seeking solutions to conflicting problems in the real world.

Unlike the strict optimization derived by mathematical programming models, which contains a single objective, goal programming was described by Garcia et al. (2010) as accepting the 'good enough'. This means that solutions derived from goal programming models are often more realistic because decision makers are interested in minimizing the unwanted deviations from set goals, which is in accordance with real world scenarios when compared to the strict solutions provided by linear programming models. With goal programming, penalties for missing the stated goals can be set; this provides the decision maker a greater view of the consequences of taking a particular action (Chang, 2008).

In a distribution environment, goal programming can be used to maximize the number of customer centers a logistics company can service, while seeking to minimize total logistics costs. Jadidi et al. (2014) used goal planning for supplier selection and order allocation under supplier capacity constraints. Liang (2010) used a fuzzy goal programming technique for project management decision making, with multiple and conflicting goals in an uncertain environment. The fuzzy goal programming technique was used in this case in order to handle the problem of incomplete and unavailable information that project managers are frequently faced with.

The allocation of appropriate weights in the objective functions is a common problem with goal programming models. Combining goal programming with AHP can alleviate this problem. Gass (1986) stated that the weights derived from the pairwise comparison of alternatives in an AHP, can be used as coefficients in the objective functions of a goal programming model, providing a better account of the weights of conflicting objectives in a goal programming model. The instance where the parameters of the goal programming model, such as goal values and coefficients, are unknown or uncertain is known as stochastic goal programming. This is closely related to fuzzy set theory, and is known as fuzzy goal programming which is mentioned above. Liu (1996) presented a methodology of solving stochastic goal programming, called dependent chance goal programming (DCGP), using genetic algorithms. This method was used in a water resource allocation and supply problem. DCGP is an option for systems in which there are multiple stochastic inputs and multiple outputs. The characteristic of DCGP, is that the chances of some probabilistic goals are dependent, and cannot be considered in isolation or converted to their deterministic equivalents.

A further criticism of goal programming is its inability to achieve Pareto efficiency in its solutions. A solution is said to be Pareto inefficient or dominated if the solution of one objective can be enhanced without harming the solution of another objective. Pareto inefficiency stems from setting goals that are too pessimistic. Tamiz and Jones (1996) presented a method of isolating and testing the Pareto efficiency of objective functions in a goal programming model. If an objective function is deemed to be Pareto inefficient, then the entire model is expected to be Pareto inefficient. This method can be used to optimize allocation and distribution strategies in public, or privately funded projects where there are severe budget constraints. Pareto inefficiency leads to questions about the long term sustainability of projects. This must be addressed as sustainability is one of the cornerstones of achieving product deployment success in a rural setting.

### *2.4.5.3 Fuzzy Analysis*

Fuzzy set theory, as presented by Zadeh (1965), alternatively referred to as fuzzy logic, is concerned with modelling the level of truth that a particular outcome belongs to a particular classification. This theory is suitable to model the vagueness of preferences that are part of human decision making, it allows uncertainty in decision making by letting the decision maker input a range of quantitative preferences for a specific criteria. Fuzzy AHP allows a decision maker to make more than one quantified preference for a specific alternative. Fuzzy set theory allows us to model the various viewpoints of decision makers and also determines if a particular water treatment system is not only favoured by decision makers but is also appropriate for a certain condition (Zadeh, 1965).

Traditional logic theory involves thought that is based on binary sets. The binary sets have two valued logic, true or false, yes or no, zero or one. Much of the information that we come across and process in real life is not as crisply defined but instead involves some type of un-sharpness (fuzziness). The level of truth that a something, be it an object, word, function or data, belongs in a particular pre-determined set may range between completely true or the completely false value. This leaves space for partial truths.

The crucial idea in fuzzy logic is to allow partial truths to stand out and to numerically describe them using a specific function (membership function) (Jayawardena et al, 2014). The membership functions take values between 0 and 1. For example, the discharge in a river may be perceived as high or low without a precise knowledge of the quantitative flow rate (Jayawardena et al, 2014). In this case the concept of ‘high’ or ‘low’ is subjective and context dependent. This necessitates the need to develop a membership function within which the concepts of “high” and “low” can be quantified. This is done using truth values where the question asked is how true it is, in terms of percentage (between 0 and 1), that the flow rate of the river is high or low. This decision is made using subject matter experts and relevant data (Jayawardena et al, 2014).

A fuzzy set is represented in a similar manner to a classical set with a few allowances. If $X$ is the universe of discourse and $x$ is a specific element of $X$ then a fuzzy set $A$ defined on $X$ is written as a collection of ordered pairs (Melin and Castillo, 2014)

$$A = \{ (x, \mu_A(x)) \} \qquad x \,\varepsilon\, X$$

Where each pair $(x, \mu_A(x))$ is an ordered pair. In a classical or crisp set singletons are only $x$ but in fuzzy sets it is made up of 2 components $x$ and $\mu_A(x)$. For instance the set $A$ may be represented as:

$$A = \{(1, 1.0), (3, 0.7), (5, 0.3)\}$$

The last element of set $A$ expresses that the number 5 belongs to $A$ to a degree of 0.7 or 70 percent.

Fuzzy rules are developed after the creation of membership functions. Fuzzy rules are developed to aid decision makers to make an appropriate choice given various alternatives. A typical fuzzy rule contains the statement ‘IF–THEN’. The first part starts with “IF” and ends before “THEN”, this is referred to as the antecedent. It combines the subsets of input variables. After the ‘THEN’ comes the consequent part, which includes the convenient fuzzy subset of the output based on the antecedent par (Jayawardena et al, 2014)t. For example “IF rainfall is high AND soil moisture is high THEN run-off is high”. Fuzzy rules are developed from individual membership functions of criteria

Membership functions, along with the fuzzy rules that are developed from them are used as inputs into a neuro-fuzzy system. Neuro-fuzzy systems synergize the human-like reasoning of fuzzy systems (i.e. membership functions and rules) with the connectionist structure of neural networks, of which the Adaptive Neuro-Fuzzy Inference Systems, or ANFIS (Jang, 1993) is the most prevalent. ANFIS uses a set of rules and suitable membership functions for a set of input–output pairs that minimize the output error using a combination of back-propagation (BP) and least mean square procedure to train the network (Jayawardena et al, 2014).

Fuzzy inference system (FIS) maps a given input to a resultant output using fuzzy logic. It can be thought of as the rule evaluation of a fuzzy system. A FIS can be thought of as consisting of three stages. At the input stage, the input variables are mapped to appropriate membership functions. At the processing stage, the rules are summoned to generate outputs for each rule. This is then combined in a particular manner to obtain an overall result for all the rules. At the output stage the pooled result is converted to output values which are then considered as the end product. There are four popular inference mechanisms in fuzzy logic systems: Mamdani (Mamdani and Assilian, 1975), Takagi–Sugeno–Kang (TSK) (Takagi and Sugeno, 1985), Tsukamoto (1979), and Larsen and Yager (2000). Of these, the most common used ones are the Mamdani type and the TSK type. Both of these systems are supported by the Matlab Fuzzy Logic Toolbox. The Mamdani FIS originally developed in 1975 to control a steam engine and boiler combination has experienced some alterations but the fundamental concepts endured (Mamdani and Assilian, 1975). With this kind the output membership functions will also be fuzzy sets which require de-fuzzification after aggregation. The de-fuzzification requires finding the centroid of a two dimensional function. This is done by a form of integration. The TSK and Tsukamoto FIS types do not require de-fuzzification at the output because the outputs are presented as mathematical functions of the inputs. In the Larsen Inference System, the fuzzy implication is done using the product operator in the same way as the Mamdani type with product operator. De-fuzzification converts the resulting fuzzy outputs from the fuzzy inference engine to a number (Larsen and Yager, 2000).

There are numerous instances where fuzzy logic has been used, typically in the Asian manufacturing industries where they have been used to develop photography cameras and to control the operations of speed trains for example. Fuzzy logic has also been used in the social and economic studies. In “Warren, McCain, and Obama needed fuzzy sets at presidential forum” by A. M. G. Solo (2012) (cited in Harpeet et al, 2013) the author demonstrated how the moderator and presidential candidates in a presidential forum required fuzzy logic to accurately ask and answer debate questions. The author demonstrated how an understanding of fuzzy logic was needed to accurately ask and answer enquiries about defining imprecise linguistic terms. M.H.F Zarandi (2012) (cited in Harpeet et al, 2013) presented a fuzzy expert system for evaluating intellectual capital. This assisted managers in understanding and evaluating the level of each asset created through intellectual activities. A. M. Dixit and H. Singh (2003) (cited in Harpeet et al, 2013) presented a fuzzy inference system to automate crack detection and impact source identification (CDISI) on microchips. D. Pal and D. Bhattacharya (1992), the authors examined the reduction in human work efficiency due to growing road traffic noise pollution. Using fuzzy logic, they monitored and modelled disturbances from vehicular road traffic and the effect on personal work performance.

Hansen (2003) (cited in Harpeet et al, 2013) applied a fuzzy weather prediction system to enhance the technique of persistence climatology by past and present weather cases. Shao (2000) presented fuzzy membership functions, based on cloud amount, cloud type, wind speed and relative humidity, to create a fuzzy function of weather classification for thermal mapping.

## 2.5 Conclusion

Africa is experiencing a water availability crisis, specifically when it comes to drinking water. Through the Millennium Development Goals, the continent has tried, with limited success, to create policies and execute activities that were meant to alleviate the water crisis. Overall, these activities have failed, and hundreds of millions of sub-Saharan Africans continue face water shortages on a consistent basis. Failure has largely been due to inconsistent policies and an inability to execute on water implementation projects. The impact of this failure is disproportionately felt in rural Africa.

The centralized water distribution systems, that are more popular in urban communities, are harder to implement in rural areas due to the tendency of rural populations to be more scattered when compared to centralized urban populations. This, among other factors, makes the implementation of a centralized water distribution system costly.

Household water purification systems have been identified as the preferred alternative to providing safe drinking water to rural African populations. There is a prevalence of water treatment systems in the market at present; this has created an evaluation and selection problem for stakeholders. This is particularly when stakeholders are constrained by specific socio-cultural and economic constraints. This methodology analyses the end to end supply chain processes that delivers these systems to rural areas and takes into account the unique criteria presented by rural African environments, such as accessibility, risk, effectiveness, cost, service level, and speed of delivery. Three systems were selected (SIPP, BSFZ, borehole systems) after an analysis of the available water treatment systems. These systems will be analysed against each criteria to determine their performance. Finally the performance data will be used as an input into the MCDM models.

# Chapter 3

# Demographic and Drinking Water Coverage Trends in Makwane Village

## 3.1 Introduction

In 2014, the World Health Organization and UNICEF's report indicated that the Millennium Development Goal (MDG) drinking water target coverage of 88% was achieved in 2010. Between 1990 (76%) and 2012 (87%), there has been an increase of 2.3 billion people who had access to an improved drinking water source, worldwide. The report also indicated that 56 % (four billion people) had access to a piped drinking water connection on their premises. In spite of these important gains there are more than 700 million people who still depend on non- improved sources of drinking water, and nearly half these people reside in sub-Saharan Africa (WHO/UNICEF, 2014). The report highlighted the disparities that exist between urban and rural areas. It is stated that 82 % of the world's population, without improved drinking water sources, live in rural areas mostly constituted of the poor people (WHO/UNICEF, 2014). This disparity is also real in South Africa, where rural communities, especially those living in scattered areas, are negatively affected by the lack of clean water provision.

When safe drinking water is available to all, it automatically reduces the health and economic costs to the communities. However, in scattered communities, the availability of water sources comes with costs, as it is often a sizeable distance away from the household. This results in copious amounts of time spent collecting water. Women and children are the primary victims as they are tasked with collecting water, while this time could be spent pursuing more value adding activities. Valuable time and energy are spent on efforts to secure a reliable water supply; whereas minimising this time could potentially allow community members to spend more time on areas of their lives that could uplift them economically, or otherwise.

When water is available in rural areas, it often presents itself in a polluted state (WHO, 2003). The sicknesses caused by impure water presents a severe burden to the economy. The health implications brought about, through the consumption of polluted water, not only has the potential to cause human distress, but also minimises individual and collective productivity. Families experience reduced disposable income due to payments made for medical care, the valuable time spent by others taking care of the sick. Subsequently a large number of people within a community, especially children, perish due to a lack of clean and safe water (WHO, 2003).

Although South Africa is considered a middle income country, there are many pockets of communities within the country that experience the conditions mentioned above. A large number of rural residents, in South Africa, experience a daily lack of clean water, even though there are resources that can be used to alleviate this problem. Consequently, this thesis provides a scientific solution to evaluating and selecting water purification systems in rural areas of Africa.

In order to provide solutions to this problem, an in depth analysis of the communities was conducted and documented in this chapter. Valuable data was gathered concerning the current situation in Makwane, a rural village situated in the Limpopo province of South Africa. The analysis sought to answer the questions surrounding age group distribution, income distribution, and the inherent processes used to collect water. The main theme of this analysis was to elicit user needs directly and indirectly. This is in line with keeping user needs first in the selection process of water treatment systems

## 3.2 Materials and Method

### 3.2.1 Description of the study site

The study was conducted in Makwane village, a rural community outside of Roossenekal in the Limpopo Province, South Africa. The Makwane rural community was chosen as a case study because it is largely representative of rural communities in Africa that are currently undergoing problems with potable water shortage, and water quality. Makwane village has also been the site of water related studies within the science field, particularly, water microbiology, and a pilot village for the implementation of decentralised systems by the Tshwane University of Technology Water Research Group, South Africa.

### 3.2.2 Collection of data

In order to use Makwane as a case study, some formalities had to be undertaken, which included the arrangement and execution of meetings with community leaders, as well as other important stakeholders such as the municipality. The inclusion of the community leaders from the beginning of the study ensured the success of the data capturing, and was also part of the strategy to include end users in the design and implementation of a sustainable household drinking water treatment systems deployment strategy.

Primary and secondary data was collected for the purpose of analysis. Primary data were collected in the form of a survey and questionnaire. Secondary data was collected from previous research conducted on Makwane village. A house to house data collection exercise, interviewing of the heads of each household, was carried out from July to August in 2014. Interviews were conducted by the author, with the assistance of an interpreter from the local municipality, who translated the questions into the local language. Interviews were targeted at local residents of Makwane village. The majority of interviewees were heads of the households, and in some cases, the older representatives of each household.

The questionnaire was largely structured to elicit answers concerning the process flow of water collection, including the time spent collecting water and the activities undertaken to collect water. Other questions included the water treatment methods used by the households, and the acceptance level of the initial Household Water Treatment Systems that were deployed by other researchers in order to ascertain social acceptability. The global positioning system (GPS) was used to position the location of each house and its respective water source. Over a period of two months, approximately 90 households in Makwane were visited in order to elicit answers with regard to water collection processes.

Secondary data were analysed to determine topics of village and household demographics, and end user preferences with regards to Household drinking water treatment systems (HWTS). Secondary data were collected from previous studies that used Makwane as a case study to determine the efficacy of HWTS. The secondary data contained information concerning household income, the number of residents per household, and age group distribution. The studies were conducted by the Tshwane University of Technology Water Research Group on separate occasions (Mwabi et al., 2011-2013; Momba et al., 2013).

### 3.2.3 Statistical Analysis

In order to provide clear evidence of the current situation in Makwane village, statistical analysis of the captured data was conducted. In particular, regression analysis was conducted to determine what level of correlation exists between the number of people in a household and the total household income. A linear regression model was used with the number of people living in a household held as the independent variable, while the total household income was the dependent variable. The results of the analysis are depicted in figure 3.5.

## 3.3 Results

### 3.3.1 Community Demographics and Income Distribution

Makwane village was separated into four distinct zones called: Lepururu, Nkakaboneng, Dithakaneng, and New Stand. There were a total of 120 households in Makwane Village of which 90 were visited and interviewed, giving a sample population of 75 %. The 90 households sampled consisted of a total of 496 residents. Figure 3.1 depicts the age distribution in Makwane village based on the gender of residents. Of the 90 households interviewed, it was discovered that a large proportion of Makwane village residents were adults between 22 to 55 years of age. Females between the ages of 22-55 made up 19.2% of the sampled female population, while males in this age group made up 16.2% of the male population.

The second most populous age group was the 0-5 year age group. The females in this age group made up 9.2% of the total sampled female population, while males made up 11.4% of the total male population. Overall, 30.2% of the male population was below 21 years of age, while 25.7 % of the female population was below this age category. Further, only 3.5 % of the male and 4.5% of the female population were 56 years old and above. The youthfulness of Makwane village was synonymous with the general South African population demographics and African population demographics as a whole. A youthful population brings about questions of access to education and economic activity.

Mapochs combined school was situated in the Dithakaneng zone within Makwane. The school hosts pupils from grade one to grade 10. All pupils at this school resided in Makwane village. After grade 10 pupils continue their schooling in Roosenekal, which was seven kilometres from the village. Opportunities for tertiary education are limited for Makwane residents due to affordability and the distance, but some residents do manage to attend tertiary institutions using bursaries and scholarships. Overall, the study showed that in a household containing an average of 5.76 residents, almost two of them attended some form of schooling. This was usually the children below the age of 12 who also average almost two per household. Table 3.1 below depicts the number of residents attending an educational institute. Almost 36% of Makwane residents attend some sort of educational institution; most of them are in high school. This correlates with the high number of youths that reside in Makwane.

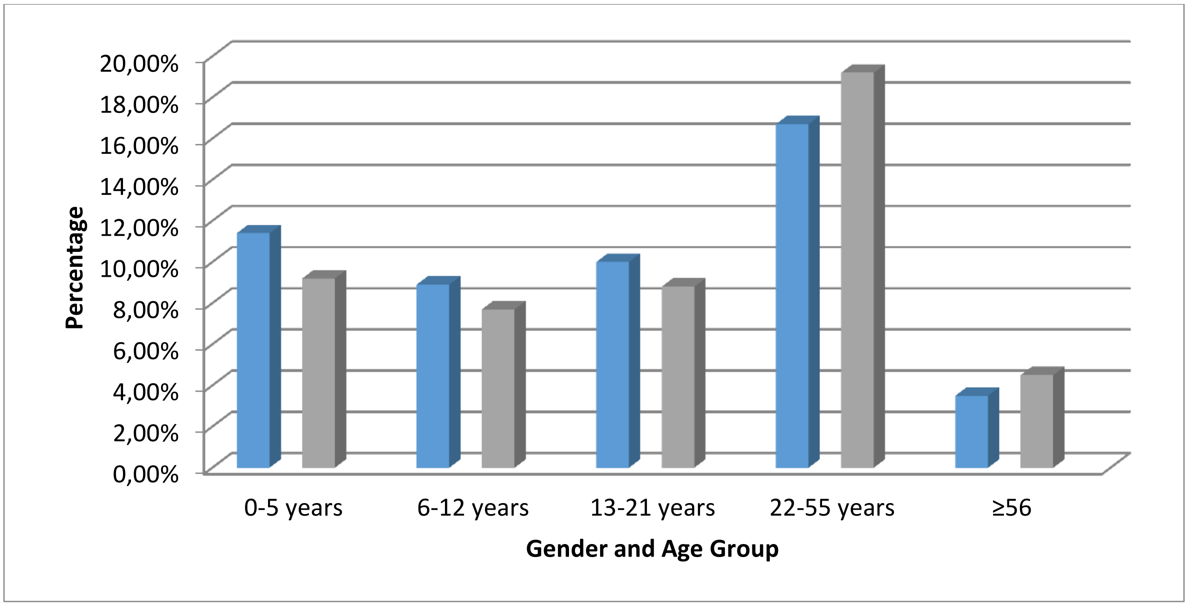


*Figure 3.1: Gender and Age Group Distribution of the Community of Makwane Village. Legend - Blue: Male, Green: Female*

*Table 3.1: Educational Institute Attendance*

| Type of Educational Institute | Percentage of residents attending school |
|---|---|
| Home Care Centre | 3 (0.6%) |
| Pre-school | 16 (3.3%) |
| High school | 153 (31.4 %) |
| College/Technikon | 2 (0.4 %) |
| University | 1 (0.2 %) |

Figure 3.2 illustrates the sources of income stream distribution in the Makwane village. The average household income at Makwane was found to be approximately R2092 per month, which translated to an income of R487 per capita, per month. The amount mentioned above equated to approximately R16.23 per day, per person. This amount was below the poverty line of $1.25 per day (R18.02 as per 9 August 2015), meaning that the residents of the Makwane were in need of an injection into the economy to bring them out of poverty. Household income is derived from varying income streams, the most common being social grants (government welfare). Social welfare played a

substantial role in providing an income to the Makwane residents, where 40% of households collected some form of social welfare. This source of income was provided in the form of child grants and pensions. The next largest income stream was income received from the salary of a household member (19%), followed by the income received from relatives outside the household (17 %). Income received from a business accounted for 11% of all households. The areas of business undertaken by Makwane residents include small scale cattle and vegetable farming. There was also a single small goods store which sold groceries. Some household members are either employed by the nearby mines, or are employed in town. Two households interviewed, lacked a discernible income stream

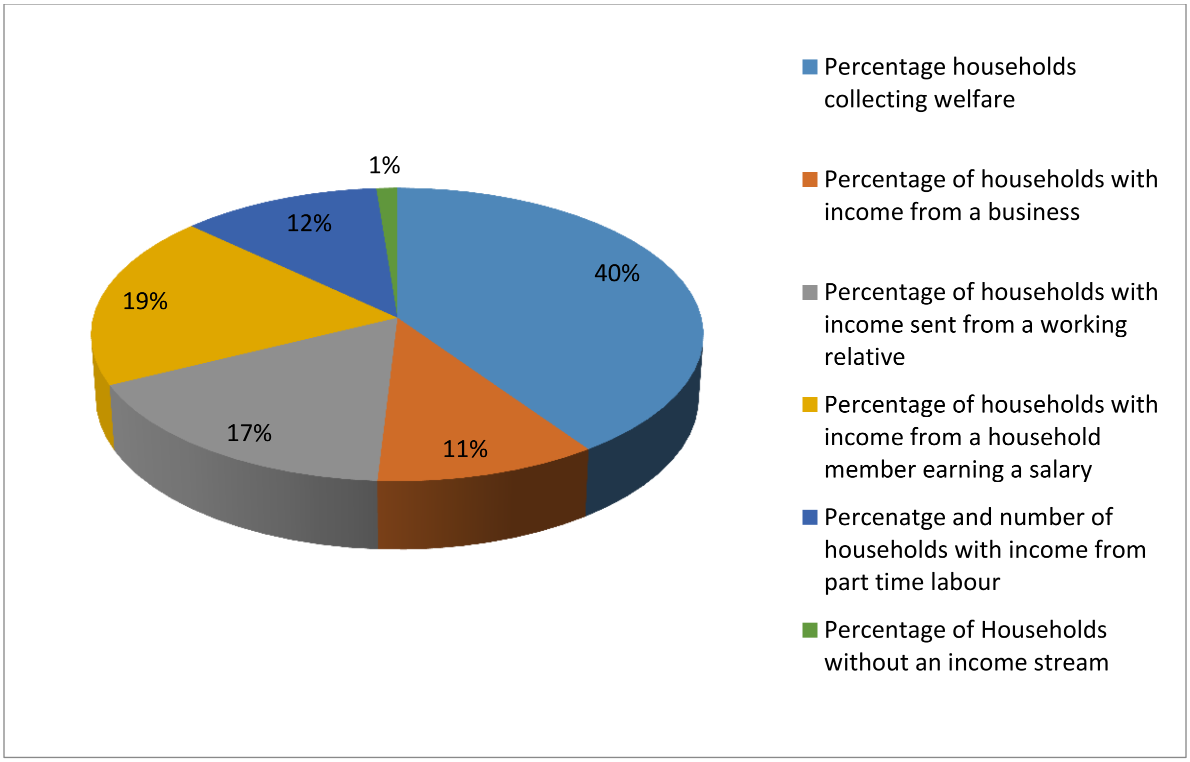


*Figure 3.2: Sources of Income Stream Distribution of the Makwane community*

Figure 3.3 depicts the income distribution streams of Households in Makwane village. A little over half (53 %) of the households interviewed had only one income stream, which was often government welfare. The results also showed that 45 % of the Makwane households had two to five income streams that allowed them to cover their monthly needs. The most deplorable situation is that two percent of the households were without any income stream.

Figure 3.4 depicts the average income of a household against the number of income streams. A positive correlation was found between average income per household and the number of income streams per household. Households with five income streams provided the exception. The average income for households with five or more income streams was R1800; this was found to be lower compared to the total average household income of R2092, or the average income of households with four income streams (R3700). The reason for this discrepancy may be because none of the income streams used by these types of households were of a permanent or recurring nature. It could also be argued that these types of households have five different income streams, because each stream brings in a minimal amount of income.

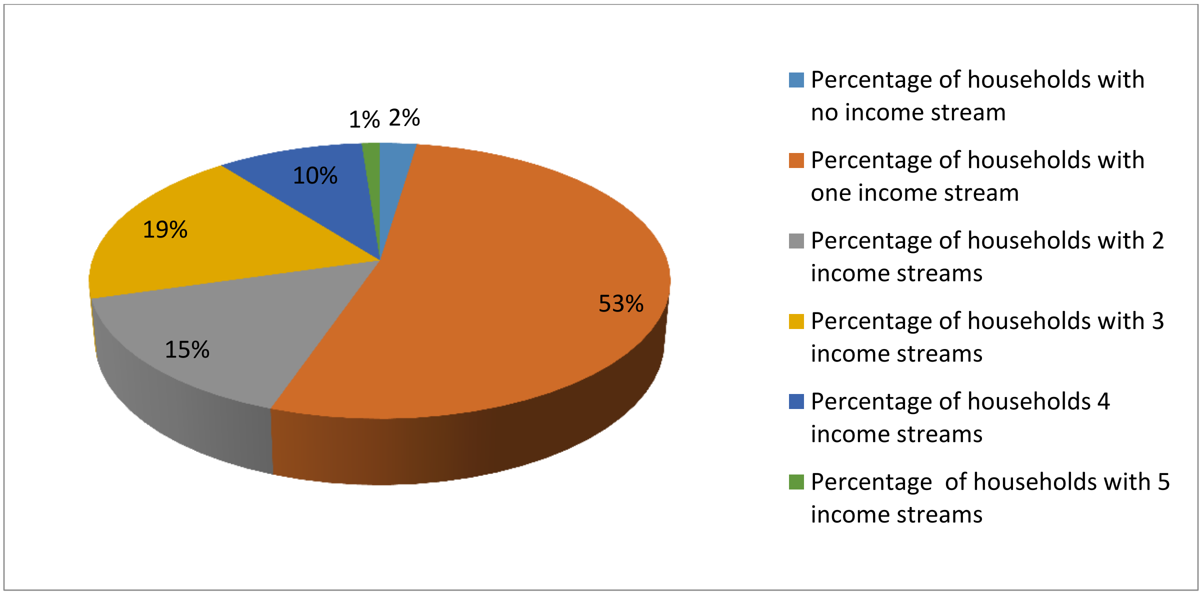


*Figure 3.3: Household income streams in the Makwane Village*

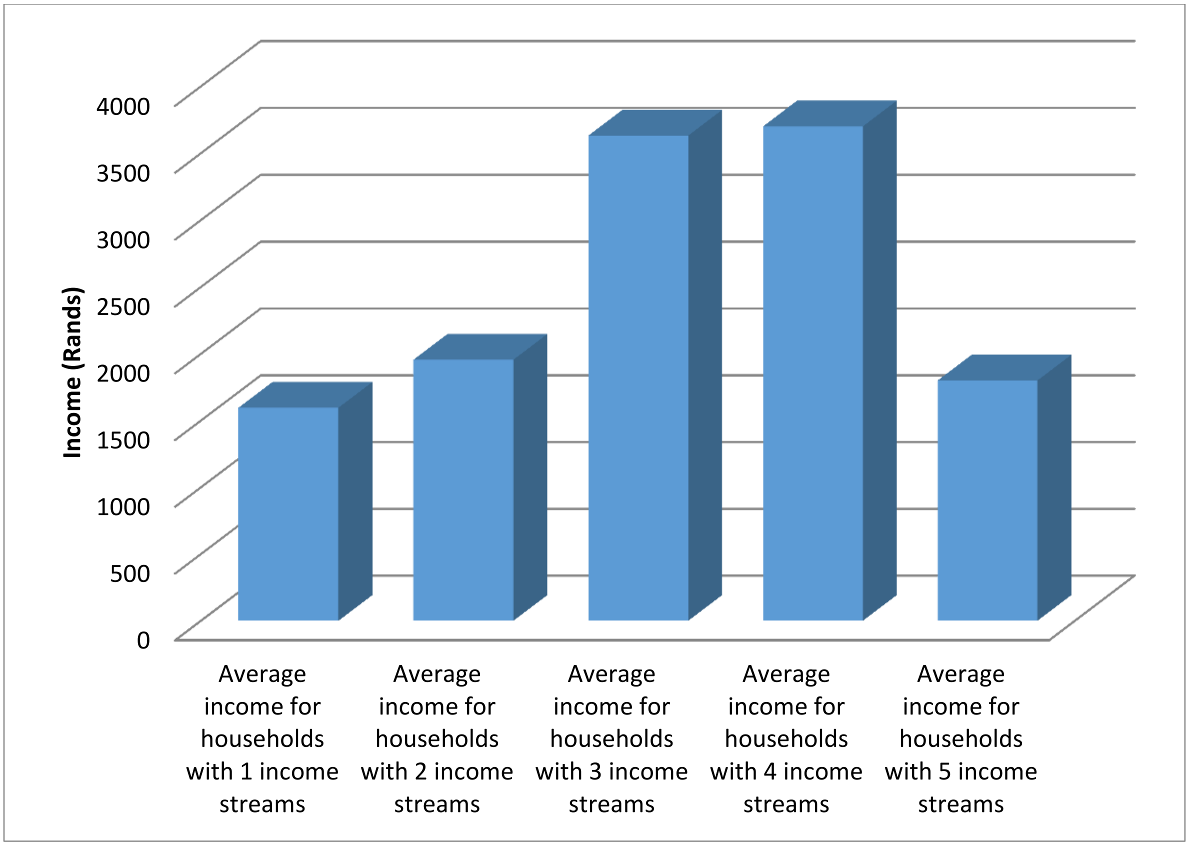


*Figure 3.4 Average income versus number of income streams*

Figure 3.5 plots the number of people, per household, against the household income. It was worthwhile noting that the number of people residing in a house did not necessarily correlate to the household income. Linear regression analysis was used to determine how close the data fits to the regression line. The $R^2$, also called the correlation of determination, stood at 2.18%, which proved that there was little correlation between the number of people in a household, and household income. When looking at Figure 3.5, one can notice that the houses with the highest levels of income were often those with fewer residents.

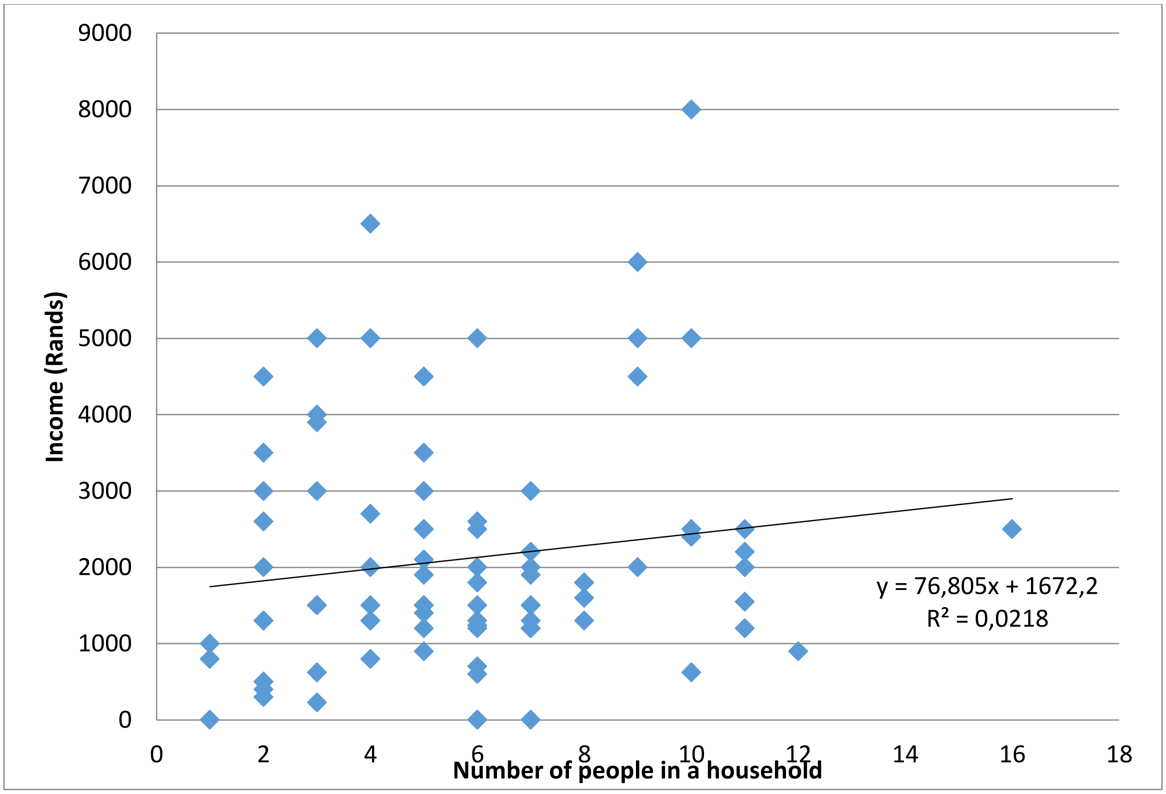


*Figure 3.5: Number of people in a household versus household income*

### 3.3.2 Water Collection Processes

The Makwane residents procured their drinking water from various sources, though the final quality of the water was questionable (Mahlangu, 2010). There were three major sources of drinking water in Makwane, namely: river water, water from a natural spring, and borehole water. Residents often use all three sources for their water requirements. Residents have designed methods to procure water from the three major sources by forming water catchment areas where all households have access to the water. Pipes have been connected from the river to communal areas, where they can be accessed by numerous households. In some cases, these pipes lead to tanks, which store the water. Similarly, water was also collected directly from a spring, and in some cases, pipes are connected from the spring to communal areas, and the water is accessed through taps. In limited cases, boreholes have been built by the local municipality. The water was usually collected in 25 litre buckets, typically by the women of the households.  Figure 3.6 below, depicts the various water catchment areas available to the village residents, and the percentage of households using each water catchment area.

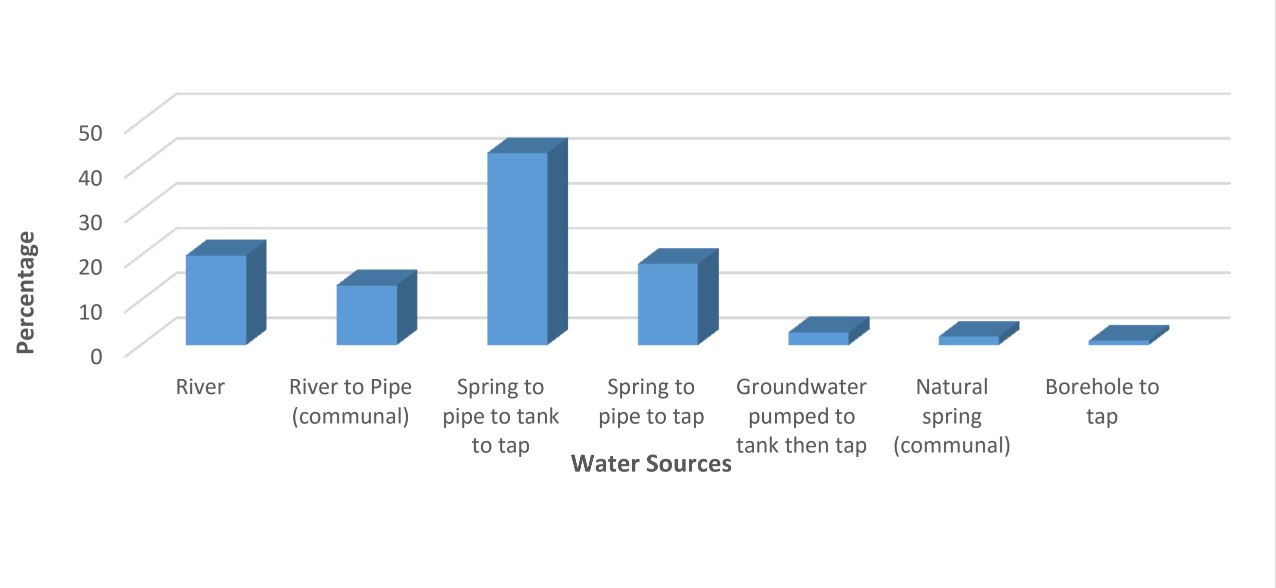


*Figure 3.6: Water Collection Process Types in the Makwane Village*

The most used catchment area was water sourced from the natural spring and is transferred to a tank using a pipe, thereafter, the water is collected from the tank (called Jojo tank) using a tap. It was found that 45 % of the households use this catchment area for collection. Overall, approximately 63 % of households use water sourced from a spring, though this water remained uncovered, and it is also used by both wild animals and livestock, as well as for washing. The Makwane River was the second most prominent water source type in the village. Water was either sourced directly at the river, or there were pipes that connected to the river to deliver water to communal catchment areas.

Overall, 35% of households used the river as the primary source of water. Other catchment areas included groundwater and boreholes. The ground water was pumped to a tank and collected using a tap. Boreholes are usually housed at individual households. A large amount of time and energy was spent collecting water daily, and water collection points are often away from the household. Figure 3.7 depicts the distances travelled by household members to collect water.

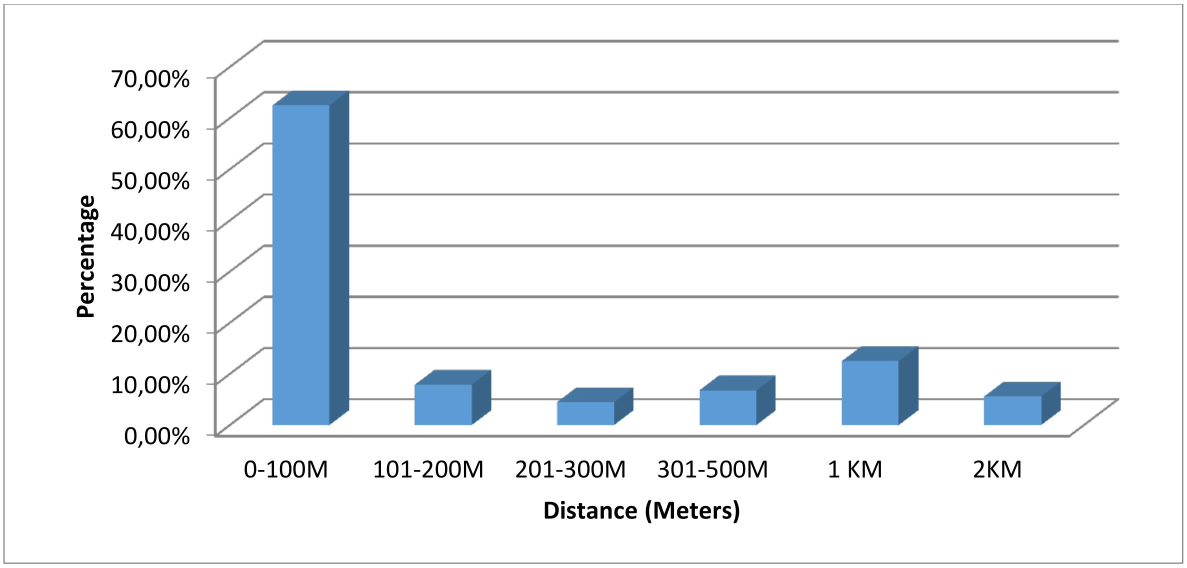


*Figure 3.7: Distance from the collection point to the household at Makwane Village*

The average distance to a collection point was found to be 372 metres. The maximum distance travelled by a household member to collect water was 2 km, with the minimum distance being 1 metre. Over 60 % of households travelled less than 100 metres to the water collection point, though a sizeable number of members walked distances between 200 metres and 1 Kilometre to collect water. Households collected water at least twice per day. The deployment of HWTS in Makwane would help to minimize the amount of times household members collect water per day.

Though Makwane Village is a single community, the individual households were scattered. Even though the village is already separated into four different zones, households remain scattered within these zones. Figures 3.8 to 3.11 below, depict the Geographic Information System representations of the households in each zone (depicted in blue circles), along with the catchment areas where households collect water (depicted in red diamonds). One notices how far households are from each other; households are on average 200 metres away from each other in three of the four zones. The exception is the New Stand section, where there are approximately 60 houses that are in close proximity and share a single collection point. This collection point sources water from a spring that is connected to a pipe, the water is stored in a tank and collected by household members using a pipe.

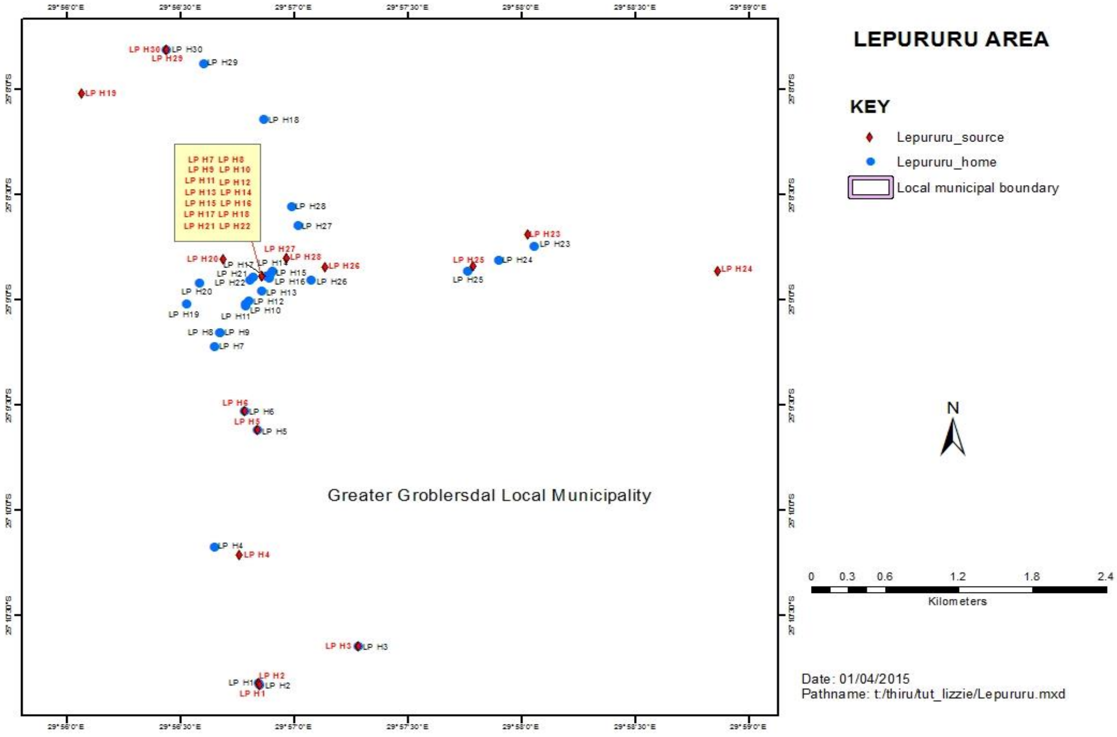


*Figure 3.8: GPS coordinates showing water source available for various Households in the Lepururu section*

Lepururu and Nkakaboreng are mountainous areas, with average altitudes of 1500 metres above sea level. These are the two sections where distances between households and water collection points were found to be the furthest. Many of the households were erected on steep inclines, therefore, one would have to climb down to get to the water collection point, and then climb back up with a water filled bucket. In some cases one would walk for 200 to 300 metres up a 60 metre incline to collect water, this process is not ideal.

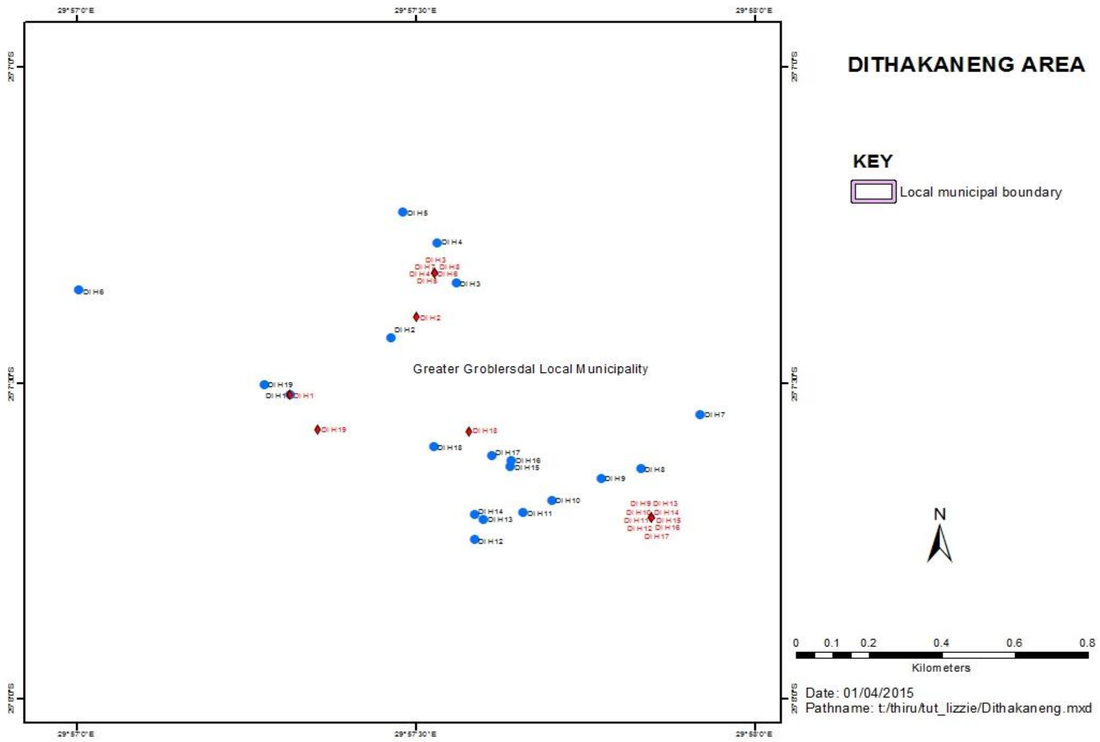
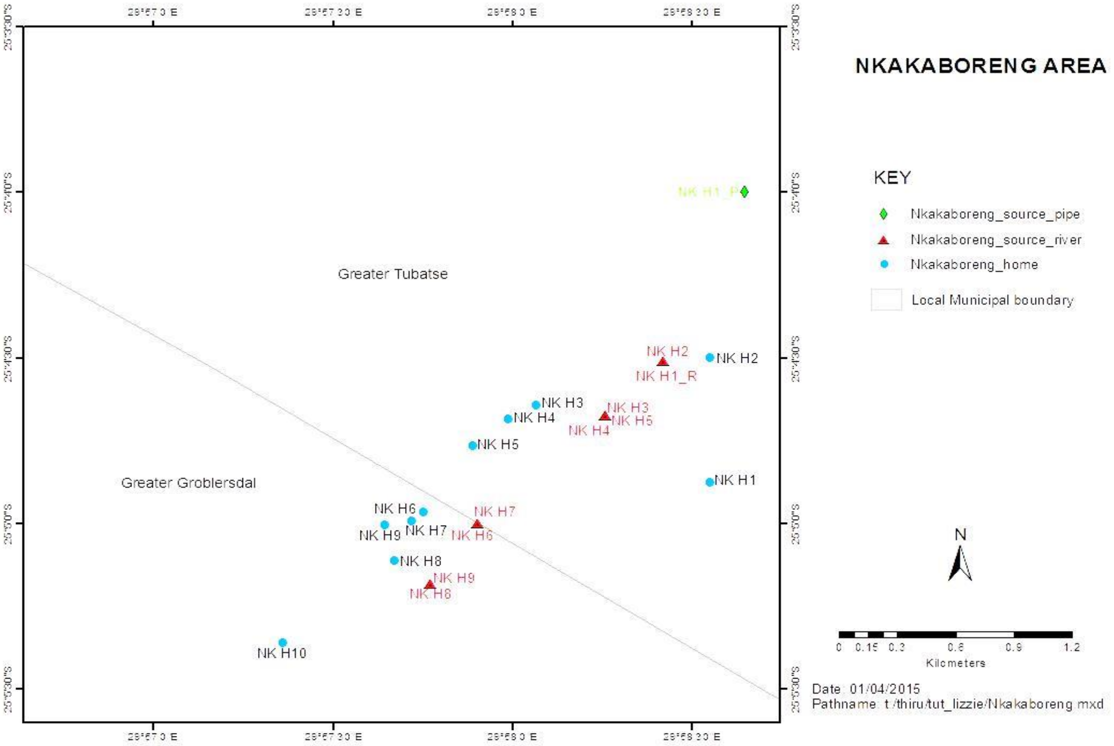


*Figure 3.9: GPS coordinates showing water source available for various Households in the Dithakeneng Section*



Date: 01/04/2015
Pathname: t:/thiru/tut_lizzie/Nkakaboreng.mxd

*Figure 3.10: GPS coordinates showing water source available for various Households in the Nkakaboreng section*

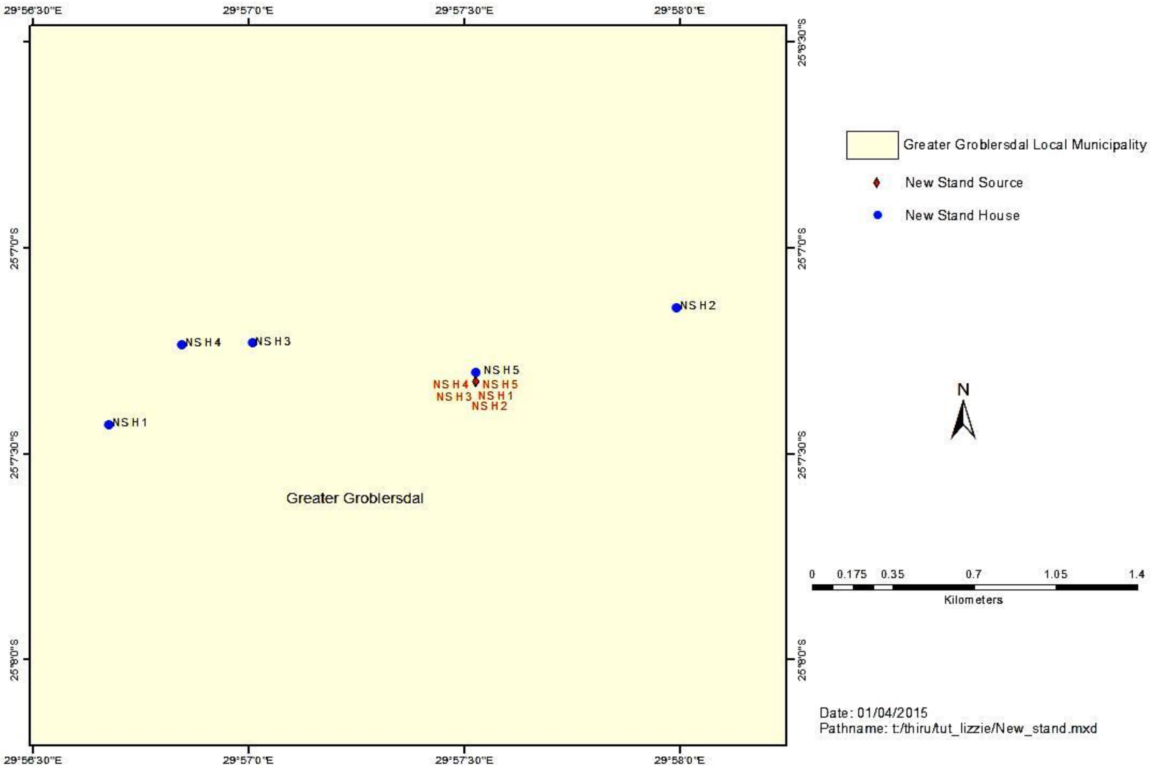


*Figure 3.11: GPS coordinates showing water source available for Selected Households in the New Stand Section*

### 3.3.3 Water Treatment Processes

Most of the households in Makwane extended little effort in purifying water to make it suitable for drinking, as evidenced in Figure 3.12. Almost 80 % of residents reported that they do not treat their water after collecting from various collection points. Almost 11 % of the residents reported that they use liquid bleach (one tea spoon in 25 L water) to disinfect their drinking water prior to use, and the remaining households boiled their water.

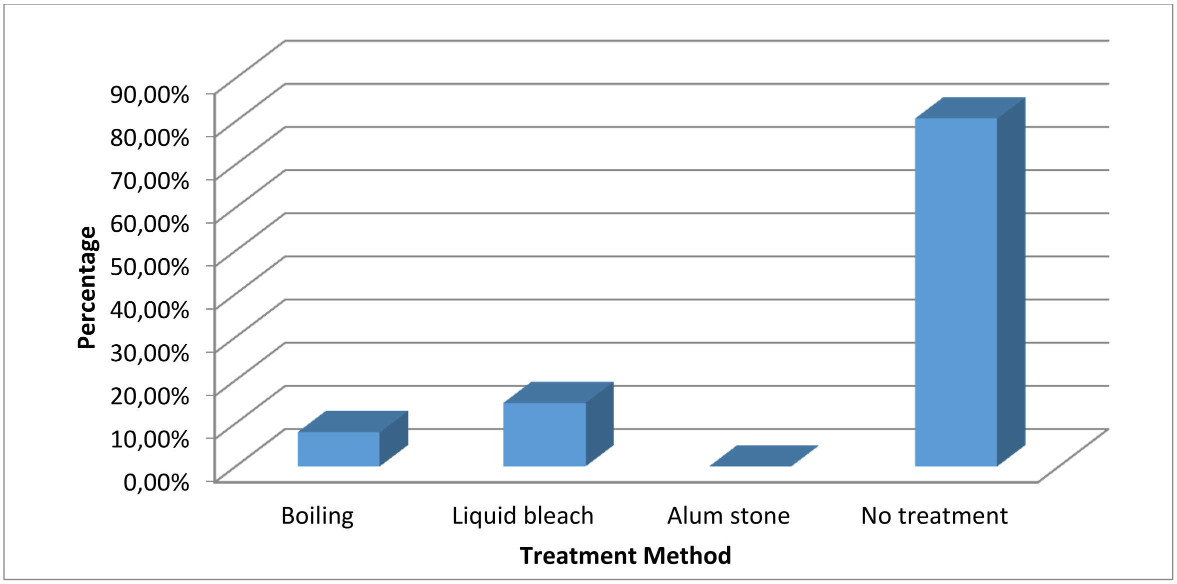


*Figure 3.12: Water Treatment Methods Used*

## 3.3.4 Health Incidences in Makwane Households

The direct result of overlooking treatment had led to the situation depicted in Figure 3.13 below. In terms of health outcomes, the most prevalent health incidence was found to be diarrheal disease (75%), which occurred mostly in children less than five  years old, and persisted up to 3 days per week (34%). Seventeen percent of the Makwane residents were also affected by hot tub rush. In spite of their low rates, trachoma (2.2 %) and body lice (3.4%) were also prevalent in the community.

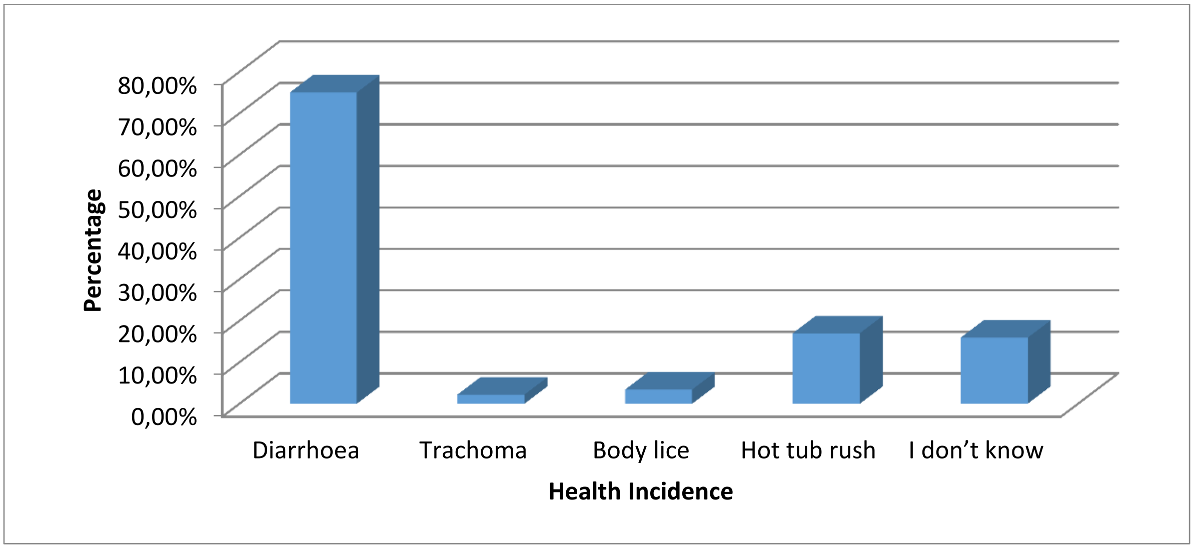


*Figure 3.13: Health Incidences in the Household*

A large number of health related problems in small rural communities means that sick residents spend a lot time not contributing to the economy. Small rural economies cannot afford to have adult residents not contributing to the economy for extended periods. Therefore, these health incidences, once again, highlight the need for the selection and implementation of household water purification systems in rural areas in order to alleviate health issues that affect the economic development of the community**.**

### 3.4 Discussion

The main objective of the MDGs was to advocate the principles of human dignity, equality and equity, and free the world from extreme poverty. The target 7c aims to reduce, by half, the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015’’ (United Nations General Assembly, 2000).

The Household survey has resulted in scientific evidence of the current demographic and drinking water status, and other indicators in the areas of education, household income, and health in the Makwane Village. The outcomes of this study have revealed that the Makwane Village is constituted of a very youthful population, with approximately one third of the sampled population being below the age of 12. These findings are consistent with studies conducted on African demographic trends, which showed high birth rates and decreasing mortality rates throughout the continent, particularly in sub-Saharan Africa (Mubila, 2012).

In sub-Saharan Africa in particular, it has been reported that 42% of the population was below the age of 15 (Sippel et al., 2011). This implies a youthful, but also a growing population in the coming decades. A youthful population was one of the determinants governing sustainable economic growth, though economic growth is possible only if the correct policies are pursued within the country. Sippel et al. (2011) noted that wherever the number of school children grow faster than the prospect to deliver this younger generation with schools, health care, food, and jobs, the economic situation of the entire country can decline. This is the case that Makwane village in particular, and African villages as a whole, are currently facing.

Education is the key for capacity building, skills development, job creation and eradication of poverty. While South Africa's policy has introduced free education, especially for black citizens from disadvantaged areas, evidence from Table 3.1 shows that only 36 % of Makwane Village’s youth attended an educational institute. The implementation of a deployment system for water treatment products in Makwane will help with the skills transfer and development of Makwane residents. This is specifically in the material sourcing and manufacturing processes, as residents can take over the execution and management of these processes.

The community was facing challenges to address the high rate of unemployment among the youth. Subsequently, the residents of Makwane village are heavily dependent on the government for survival (Figures 3.2-3.3). The study also showed that families with two or more income streams usually had an employed member of the household who earned a regular salary. Sometimes the family engaged in small scale vegetable or livestock farming to supplement their income. External family members who lived outside of Makwane would also regularly send money to supplement incomes. Households with at least five sources of income were in the minority (Figures 3.2- 3.3).

The average household income at Makwane was approximately R2092 per month, which translated to an income of R487 per individual, per month. Household income was derived from a number of streams ranging from welfare to small scale farming. This was slightly better than average household income in the Eastern Cape Province of South Africa, which stood at R1276 per rural household (Westaway, 2010). Further, more than half of the rural population of the province lived on less than R220 per person, per month. These low levels of income are synonymous with the plight of communities throughout South Africa. As South Africa is considered a middle income country by the WHO, one can deduce that other African countries fare a lot worse when it comes to rural household income. The 2014 United Nations Report on MDG showed the overwhelming majority of people living on less than $1.25 a day reside in Southern Asia and sub-Saharan Africa. Nearly two thirds of the extreme poor lived in the following five countries in 2010: India (alone having one third of the world’s 1.2billion extreme poor alone), China (13 %), Nigeria (9 %), Bangladesh (5 %) and the Democratic Republic of the Congo (5%) (United Nations, 2014). Rural sub-Saharan Africa continues to confront a tremendous challenge in addressing the rate of unemployment of its population, and South Africa is not an exception.

Employment and income data by country and by sector of activity is uncommon, and is often not disaggregated between rural and urban economies. This makes the current organisation of rural employment in sub-Saharan Africa, and the subsequent trends in employment, difficult to evaluate and compare (Procter, 2014). It is notable, however, that agriculture overall, in spite of variances between countries and regions, remains the largest employer in sub-Saharan Africa at approximately 59 percent of the total number of people in employment in 2009 (Procter, 2014). This is consistent with observations in Makwane Village where livestock and small scale crop farming remain the largest form of income outside external family and government subsidies. Rural South African communities are in a fortunate position where they can claim government welfare, whereas this is not possible in other countries.

Any project that seeks to improve the livelihood of rural residents must have affordability as the central criteria. The low level, average household income in Makwane Village means that residents cannot afford expensive clean water related implementation projects. Furthermore, these programs are often not sustainable in the long term due to the high level of costs necessary to keep its operations going.

The survey, in terms of drinking water coverage trend, revealed that 63% of the Makwane Village residents rely on unimproved water sources from an unprotected spring, and a further 35 % collect their drinking water from the river. This is consistent with studies conducted in other rural areas of South Africa, where approximately four million people still obtain drinking water from rivers and springs without any preceding treatment (Mackintosh et al., 2000). Due to the lack of infrastructure in rural areas, members of rural communities depend on any water source available, ranging from unprotected hand-dug wells, springs, rivers, and streams that are often of poor quality for their drinking water (Momba et al., 2006; Busari, 2007).

Treatment of drinking water is crucial for the production of safe drinking water. If only one barrier is possible to remove, disinfection should be considered as the most important method, unless evidence exists that chemical contaminants are more harmful than the risk caused when ingesting microbial pathogens. At Makwane Village, approximately 22 % of households treat their drinking water prior to use. Boiling and chlorination by liquid bleach were found to be the two drinking water treatment methods used by this portion of the Makwane Village residents (Figure 3.12).

The boiling water process remains the most common water treatment method, and is the benchmark against which alternative household based disinfection and filtration is measured. Boiling significantly improves the microbiological composition of potable water, and is a relatively reliable form of water treatment (Clasen et al., 2007). In a study of rural communities in Vietnam, boiling was found to be the most common form of water treatment. This is common among communities who are aware of the detrimental effects of drinking water, but do not have the resources to pursue more expensive water treatment methods (Clasen et al., 2007).

Though Clasen et al. (2007) suggested that boiling significantly improves the microbiological content of water; it does not fully remove the risk of water borne pathogens. In a study conducted in rural Vietnam by these authors, 60.5% of the stored boiled water samples tested positive for thermo-tolerant coliform.

Drinking water treatment has not been taken up by the majority of the residents of Makwane Village, as evidenced in Figure 3.12. This could be due to the lack of awareness concerning the purity of water in Makwane, as well as the relatively high price of the wood used to boil water. It is also notable that Makwane residents do not use other cheap treatment methods, such as bleach, to disinfect water. Therefore, one may conclude that it may be necessary to create more awareness of the quality of the water in Makwane Village, so that residents can incorporate the purchase of cheap water treatment methodologies in their spending habits. One can deduce that the lack of knowledge of water treatment systems is a result of the lack of research on the subject and, more importantly, the dissemination of this research into the affected communities. It is imperative to continue the research into water treatment systems and educate fellow Africans on the possible remedies for the treatment of impure water.

The effects of unsafe drinking water on public health are well documented, especially among young children. The WHO (2010) noted that 40% of children below the age of five will die if given unsafe water. Diarrhoea and cholera are diseases that stem from drinking unclean water. The highest percentage of deaths among children under the age of 5 years caused by diarrheal diseases was reported to be in Angola (25%), followed by Madagascar (22%), and the Democratic Republic of Congo (19%) respectively (WHO, 2010). The present study in Makwane Village confirmed the burden of diarrheal disease due to the lack of safe drinking water in the rural communities of Africa. The prevalence of this waterborne disease was found more acute in children below the age of five as their immune systems have not been properly formed yet. This situation is potentially more severe in Makwane, as a large number of the population consists of children. This study calls for a reverse situation that can lead to the development of evaluation and selection model for appropriate water treatment systems

### 3.5 Conclusion

The situation in Makwane Village was synonymous of numerous rural areas in South Africa, and Africa as a whole. The composition of the community consisted largely of number of young people below the age of 21. Economic opportunities were few, with most residents receiving some sort of government support. The lack of economic opportunities brought into question the future economic growth of the country, and the continent.

The households in Makwane Village were scattered, and the distances travelled to collect water varied, with some being less than 100 meters away and others more than two kilometres away. Almost all households did not have indoor plumbing. There were three observed water sources: a river, an unprotected spring, and some households collected water from a borehole. Very few residents in Makwane follow accepted drinking water treatment practices; many residents did not treat drinking water at all. This lack of clean water often manifests itself in sickness and disease, which is a dangerous position for young children in particular

Makwane village is the quintessential rural African village. There was a need to provide these villages with adequate service delivery. Providing water treatment systems will facilitate greater community health and economic growth. The design and documentation of a detailed water treatment evaluation and selection strategy may help to take these villages on the right path toward social and economic upliftment.

It is a worthwhile exercise to seek areas of economic development that would provide employment opportunities through skills transfer, in such a way that dependency on government financial intervention can be minimised (these economic opportunities will be explored later in other chapters). The implementation of HWTS in Makwane Village can play a part in limiting the negative impact that unclean water has on the health of the community, particularly the younger generation. Household water treatment systems can also provide a means to economically develop the community by starting a business around the maintenance and manufacture of these systems. This subject will be discussed in detail in the following chapter.

# Chapter 4

# Feasibility Analysis for the Deployment of Water Treatment Systems in Makwane Village

## 4.1 Introduction

Makwane Village, like many rural villages in Africa, faced a considerable hurdle in terms of service delivery. It was largely representative of the ongoing problems with potable water shortage and water quality. In an endeavour to provide quality drinking water to Makwane, and similar villages in Africa, it was necessary to understand how service providers, private companies and local governments, provided services to the rural areas of South Arica. More importantly, it was essential to understand the criteria necessary to assess the suitability and added value of the water deployment process in rural areas. Through interviews with key stakeholders, observation, and the perusal of available literature, four key criteria that required consideration were identified. The key criteria were deployment cost (affordability), product risk, product effectiveness, and the social impact and accessibility created by the deployment of household water treatment systems.

To select the most appropriate water treatment systems for Makwane Village, customer value, in each step of the process, must be measured. In order to do this, it was necessary to map and analyse the end to end processes in the supply chain used to deploy water solutions in Makwane. In this chapter we focused on detailing the supply chain processes required to deliver water purification systems to Makwane village. Three end to end supply chains were mapped; this represented the deployment processes of three alternative purification systems that were deemed most suitable to produce clean water for the Makwane community. Subsequently, the performance of each supply chain was measured against the criteria stated above. These criteria were chosen because, after the analysis of the supply chains of various service delivery models, it was discovered that they can be defined according to these four themes (Tayur et al., 1998; Abutakeer et al., 2012; Agarwal, 2014). The outcome of this chapter is a thorough performance study of the supply chain processes that would be used to deploy water treatment systems in Makwane.

Each criteria was allocated a set of metrics that can be used for measurement to determine overall supply chain health. The outcome is a detailed proposed deployment supply chain, complete with metrics that can be used to track supply chain measurement. Table 4.1 depicts the metrics that were used to measure the criteria. This analysis was conducted for each of the three water treatment systems under consideration. It must be noted that though all metrics were researched and analysed, not all of them were used to measure respective criteria in the final selection models. In the final model the metric used to represent risk was RPN, social Impact and accessibility was measured by the distance travelled to collect water, product effectiveness was measured by flow rate of the water treatment system, deployment costs was measured by supply chain and maintenance costs.

*Table 4.1: Metrics used to measure the Selected Criteria*

| | **Criteria** | | | |
|---|---|---|---|---|
| | **Risk** | **Deployment Costs** | **Social Impact and Accessibility** | **Product Effectiveness** |
| **Metrics** | RPN | Supply Chain Costs | Distance travelled to Collect water | Flow rate |
| | | Maintenance Costs | Skills Transferred | Microbial Removal |
| | | Design Costs | Job Opportunities Created | Turbidity Removal |
| | | | Distances to material Suppliers | |

## 4.2 Materials and Methods

### 4.2.1 Methodology

The study used operations management techniques to analyse the HWTS the performance of the selected HWTS against the stated criteria, in order to come to a conclusion about which water treatment system selected for use in Makwane Village.

The supply chain of each HWST was decomposed into processes and analysed separately against each criteria using various industrial engineering tools. A significant amount of raw data was collected in the form of surveys, and interviews with various stakeholders. This data was used as inputs into the models used to analyse the supply chain. Tools such a process mapping, specifically business process mapping notation, was used to map the end to end supply chain of each HWTS at an activity level (level three).

The failure mode and effects (FMEA) model was used to analyse potential failure modes of the proposed water treatment systems, including the causes and potential effects of the failure. The FMEA methodology identifies and prioritizes system failures according to how serious their consequences may be, how regularly they occur, and how quickly or easily they can be detected (Carlson, 2012). Then actions can be taken to reduce or eliminate failures, beginning with those of the uppermost priority. Subject matter experts (SMEs) involved in the design of water treatment systems were asked to evaluate failure modes, and its resultant causes and effects in order to produce a fully representative and exhaustive FMEA model. The SMEs included Professor Maggy Momba, who led the design phase, and is the patent holder of the SIPP and BSFZ water treatment systems. Bruce Berger and Pieter du Toit were engineers based at the Cermalab in Pretoria, both are experienced manufacturing professionals who helped with the initial production and distribution of the household water treatment systems. Finally, some members of Makwane Village, who had used the initial distribution of the treatment systems, were selected to be included in their evaluation.

The FMEA technique was used to analyse product risk, one of the key deployment criteria mentioned above. SME's were asked questions regarding failures of water treatments systems. One of the key metrics used to track risk was the Risk Priority Number (RPN). This metric is important because it helps to determine when replacement materials need to be ordered or when the product requires repairs.

The social impact study centred on the ability of the community to operate the supply chain, independent of external help, and the possible skills transfer opportunities that could be created by moving these operations of the supply chain into the hands of the Makwane community. This meant that selected village members would be solely responsible for the sourcing of input materials and the production of the SIPP and BSFZ. Learning and practicing these new skills created an opportunity for some village members to be eligible to apply these skills in the job market or create a business. University academics were questioned if the skills learnt by members of the Makwane Village are applicable in the current job market. The ability of Makwane residents to access parts required for the maintenance of the water purification systems was also analysed in the social impact and accessibility study. The study analysed the geographic areas where inputs for treatment systems were gathered, and created a network of potential sourcing areas that are in close proximity to the end user. The distances travelled by community members to collect water were also analyzed as this had a direct impact on which treatment system would be most advisable. The closer the collection distance the more likely the treatment system will operate optimally as they require constant replenishment.

The flow rate of the water purification system, and its ability to remove pathogens was the central tenet of the study of the effectiveness of the purification system. Through the use of the purification systems in a controlled environment, we were able to determine and compare factors such as flow rate, microbial removal, and turbidity.

The overwhelming criterion related to the design of most supply chains is cost. The approach to the analysis of the supply chain costs was to create a cost model that looked at the present costs associated with a single deployment of a selected treatment system, as well as multiple deployments over a 10 year period. The crucial question that would be answered was whether the proposed methods used to bring water treatment systems to Makwane Village would be feasible, both in the short and long term, for the donor concerned. Procurement, human resources, training, manufacturing, and maintenance costs were taken into account. Data was collected from input suppliers and SMEs through the form of observations and interviews.

### 4.2.2 Data Collection

The primary data collected for the purpose of analysis was used as an input to the various models that were constructed. The majority of the data was collected using questionnaires and surveys. For the creation of all models, the SMEs were questioned individually and in groups. SMEs included those who were closely involved with the design and manufacture of household water purification systems, as well as experts in borehole design and commissioning. Questionnaires were used to guide the interviews with SMEs. The questionnaires were divided into product design, material procurement, manufacturing, and testing and deployment sections. Each water treatment solution under consideration was discussed with regards to these sections including how they performed against the above mentioned criteria. The questionnaires used in the interviews are depicted in appendix C

### 4.2.3 Mapping the Water Treatment System Supply Chain

In order to analyse the water treatment system supply chain, it was necessary to map all processes involved in the supply chain of water purification systems in a high level of detail. Therefore, Business Process Modelling Notation (BPMN) was used to map all relevant processes at level three of activity. The BPMN was pioneered by business process management Institute (BPMI) as a tool to depict graphical representations of business processes (White, 2006). Mapping the processes used to deploy the SIPP and BSFZ was done on the same process map due to the similarity of the materials required for construction (they have similar suppliers). The mapping of the borehole design and construction, were done separately, as this is a completely different process and requires a separate explanation. For all three proposed treatment systems, the mapping was divided into inbound supply processes, manufacturing processes, and outbound supply processes.

## 4.3 Results

### 4.3.1. Procurement and Inbound Supply of the SIPP and BSFZ

There were 22 unique activities that constitute the procurement and inbound supply process, as depicted in figure 4.1 of appendix B. Mapping the inbound processes of the SIPP and BSFZ were bundled together due to the similarity of the processes, as well as the material suppliers, all activities in the procurement and inbound supply process were sequential in nature. These activities were broken down into three distinct zones (or swim lanes) in order to categorize them. The zones were called supplier identification, supplier classification and engagement, and material purchasing.

*Table 4.2: Input Materials Required Per Unit of the BSFZ*

| Item | Quantity |
|---|---|
| 25 l bucket | 1 |
| Spigot | 1 |
| Clear tubing | 0.5 m |
| Insert elbow (90 °, 20 mm) | 1 |
| Insert male elbow (90 °, 20 mm) | 1 |
| Thread tape | 1 |
| fine sand (0.075 - 0.3 mm) | 2kg |
| Coarse sand (0.6-1.5 mm) | 1 kg |
| Gravel (4-9 mm) | 1 kg |
| Zeolites (3 mm) | 10 kg |

*Table 4.3: Input Materials Required Per Unit of the SIPP*

| Item | Quantity |
|---|---|
| Ball clay | 1.3 Kg |
| Saw dust | 0.6 Kg |
| Paper fibre | 0.1Kg |
| Silver Nitrate (AGNO3) | 0.235g |
| 10L Plastic bucket | 1 |
| 20L Plastic bucket | 1 |
| Ceramic Mould | 1 |
| Clean water (1.6L) | 1.6L |

The activities in the supplier identification swim lane were concerned with identifying and listing all inputs required to build a water treatment system. Table 4.2 and table 4.3 list all material inputs required for the purchase of the BSFZ and SIPP. After listing all required inputs for manufacturing the BSFZ and SIPP, an internet study of potential suppliers was conducted. SMEs were engaged, in order to supplement the internet research. The SMEs were questioned to determine the most suitable suppliers for particular inputs.

The supplier classification and engagement swim lane classifies suppliers according to material cost, quality, and supplier geographic location. Care was taken to identify suppliers who provided materials at affordable cost and good quality, but who were also close in proximity to the final customer, as they would be the ones who eventually undertake the execution of all processes in the value chain. Some identified suppliers included MICA stores, Chamberlains, Limpopo Brick Clay Manufacturers, Plastillon, and Sigma Aldrich.

Material purchasing and deployment concerned itself with the actual purchasing of input materials. There were two kinds of suppliers that were identified, those that could deliver materials, and those who required materials to be picked up.

### 4.3.2. Manufacturing and Operation of the BSFZ System

Manufacturing the BSFZ system is a simple process that can be conducted by a single person, provided that they have the requisite skills for the task. Figure 4.2 in appendix B depicts all processes used to manufacture, operate, and maintain the BSFZ system. There were a total of 19 activities categorized into three swim lanes which need to be undertaken to manufacture the BSFZ system. The three swim lanes included plumbing, filter body construction, and diffuser plate construction. The processes in the three swim lanes were sequential in nature.

*Table 4.4: Tools Required to Manufacture the BSFZ*

| |
|---|
| Power Drill |
| 20 mm hole saw |
| 2 mm drill bit |
| Craft knife |
| Hardware or strong pair of scissors |
| Ruler or measuring tape |
| Pencil or black marker |

The plumbing process started with gathering the tools required to manufacture the system (Table 4.4).There were a total of seven tools required, all of which can be bought off the shelf at various hardware stores. There were seven input materials required to construct the internal plumbing of the BSFZ listed in figure 4.3. The input materials must be attached to each other in the manner described in the process flows. Care must be taken in the construction of the plumbing to ensure that all materials are securely attached. The outcome of the plumbing construction is depicted in figure 4.4. The plumbing is mounted onto the inside of the filter, and the spigot is attached from the outside through a hole in the filter bucket, as depicted in figure 4.5.

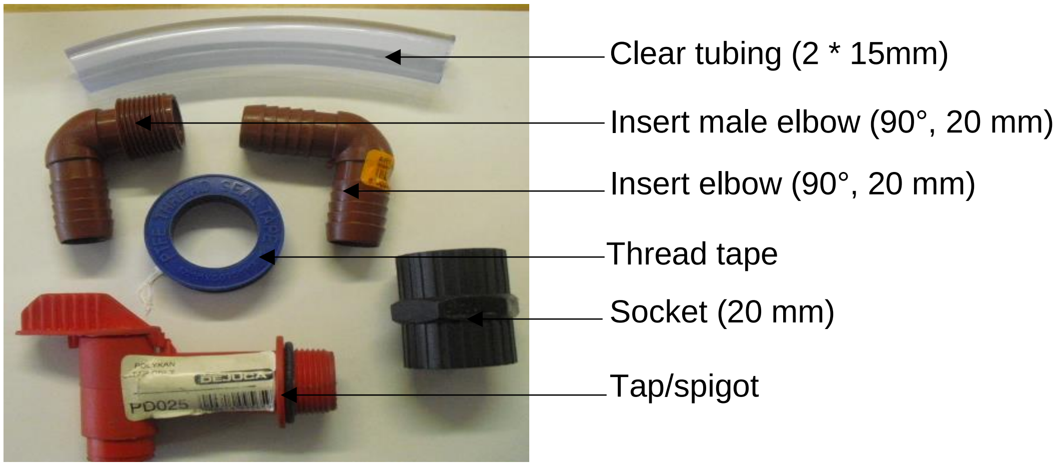


*Figure 4.3: Input materials required to construct the internal plumbing of the BSFZ*

*Source: Mwabi et al., 2012*

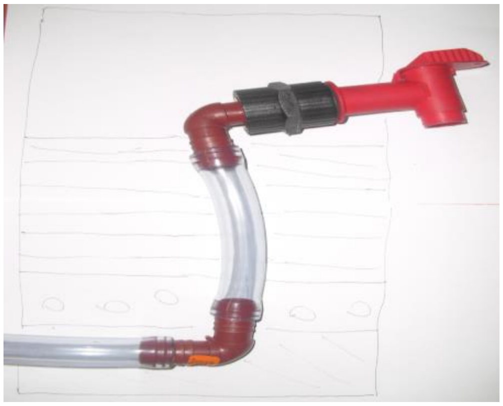


*Figure 4.4: Completed plumbing for the BSFZ before being mounted on the filter bucket*

*Source: Mwabi et al., 2012*

*Figure 4.5: Completed plumbing after Being Mounted on the filter bucket*

Source: Mwabi et al., 2012

Once the plumbing system had been mounted, the bucket was cleaned and filled with filter media, the method is depicted in the filter body construction swim lane in figure 4.2. The filter media consists of three layers of sand and a layer of zeolites. The three layers of sand are gravel, coarse sand, and fine sand. The sand is differentiated by the size of the individual grain of sand. Grains of gravel are five to seven millimeters in size, grains of coarse sand are approximately 0.95mm in size, and fine sand grains are approximately 0.15mm in Zeolites are used as an added filter media to remove certain chemical contaminants. The three layers of sand and zeolites must be washed separately prior to them being inserted into the filter media. Figures 4.6 and 4.7 depict the cleaning and insertion of the filter media into the filter bucket as described above.

*Figure 4.6: Cleaning of the Filter Media with Gravel (left), Coarse Sand (middle) and Zeolites (right)*

*Source: Mwabi et al., 2012*

*Figure 4.7: Pouring of Filter Media inside the Filter Bucket. Gravel (far left), Coarse Sand (middle left), Zeolites (middle right) and Fine Sand (far right).*

*Source: Mwabi et al., 2012*

Once the filter had been constructed, water was poured into the bucket until five centimeters resting water level above the fine sand layer develops. This will later be responsible for the formation of the biological layer, which increases the pathogen elimination competence of a biosand filter. The diffusion plate is constructed by drilling holes into the lid of the bucket. The edge of the lid was cut off so that it fitted securely against the inside wall of the filter bucket. The diffusion plate construction is depicted in figure 4.8.

*Figure 4.8: Diffusion Plate Construction. Source: Mwabi et al, 2012*

After the development of the biological layer, the (BSFZ) is ready for operation. A separate container was used to collect impure water, this was then gently poured into the top of the filter bucket and the water will be ready to use in a few hours. Clean water should be stored in a sanitary and secure storage container, and must be used within 24 hours, if possible. Water should not be stored for more than 48 hours.

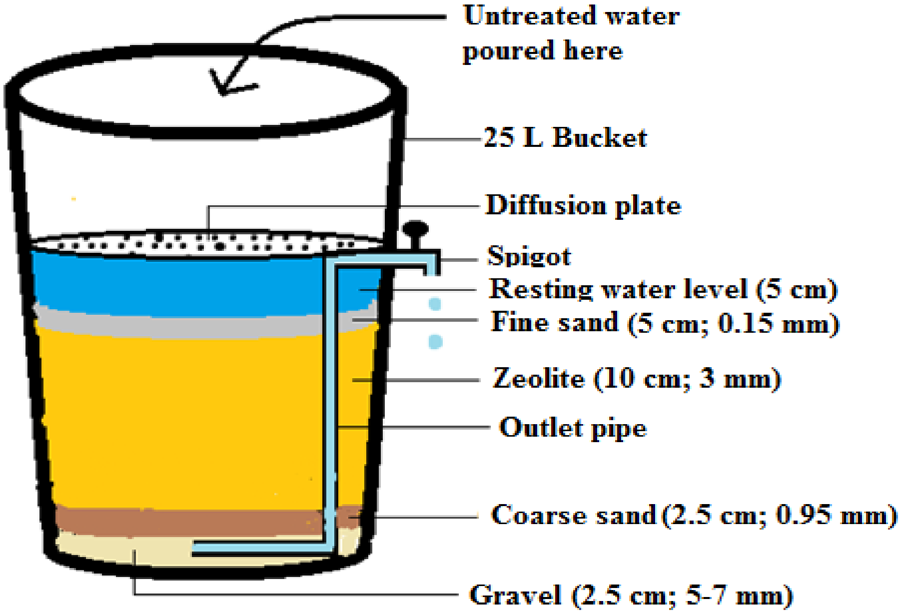


*Figure 4.9: Operation of the Biosand Filter with Zeolites (BSFZ). Source: Mwabi et al., 2012*

The maintenance procedure for the BSFZ was designed to be quick and efficient. The diffusion plate is removed, and then the top layer of sand (approximately one centimeter) must be removed, washed, and then placed back into the filter bucket. Alternatively this top layer can be replaced with fine sand. Water is poured into the filter, and the flow rate is monitored.

### Acquiring Sand and Constructing a Sieve

The BSFZ was designed to ensure that the end user can easily operate the system. Further, when looking at its value chain, it presents an opportunity for the users of the product to take over all processes within the value chain, from input material sourcing to manufacturing and operation. We will analyse this further in the sections to come.

It will not always be possible for those involved in the value chain of the BSFZ to access filter sand due to the distances of the vendors. This is especially true when one considers that a large amount of the processes conducted in the value chain may be allocated to people in the community whose mobility may be constrained. The design of the value chain must take this into account. Therefore, alternative methods of acquiring filter sand were investigated, and it was found that crushed rock can be sieved into a desired particle necessary for use in the BSFZ.

*Table 4.5: Properties to Look for when Searching for Filter Sand*

| **YES** | **NO** |
|---|---|
| When selecting sand you should be able to feel the coarseness of the grains | The sand should not contain any organic material (e.g. leaves, grass, sticks, Loam, dirt). |
| The individual grains of sand should be clearly visible, and the grains must be of different sizes and Shapes. | Avoid collecting sand from areas that have been used frequently by people or animals. |
| When the sand is squeezed and released from your hand it should pour out smoothly out of your hand. | It should not be very fine sand or sand That is mostly silt and clay. |
| Sand with a lot of gravel, no more than 8 mm in diameter, should be used. | When you squeeze a handful of dry sand, it should not ball up in your hand or stick to your hand. If it does, it possibly has a lot of dirt or clay. |

***Source: The CAWST Biosand filter Training manual September 2009.***

Crushed rock can be obtained from a gravel pit or a quarry. There is a quarry 3km away from Makwane Village. It is imperative that this sand, or crushed rock, has never been immersed in water. The sand requires disinfection by removing insects, sticks, and other debris. It must then be left in the sun for three to six hours. Table 4.5 depicts the properties to look for when searching for filtered sand. The crushed rock or sand requires a sieve to get the preferred sand to make up the filter media. For this, sieves of pore size 0.15 mm, 0.95 mm, 3 mm, and 5-7 mm need to be acquired. Table 4.6 below depicts the materials and tools required to construct a sieve.

*Table 4.6: Materials and Tools Required to Construct a Sieve*

| |
|---|
| Nails |
| 1.3 cm staples (if available) |
| 2.5 cm x 2.5 cm wood strapping |
| 2.5 cm x 10 cm wood |
| 5/7 mm mesh/wire screen |
| 3 mm wire screen |
| 0.95/1 mm wire screen |
| 0.15/0.2 mm wire screen |
| Hammer |
| Saw |
| Tape Measure |

The sieves available on the market may be too costly for rural communities to purchase. Fortunately sieves can be constructed out of bits of wood and mesh. Figure 4.10, in appendix B, depicts the activities involved for constructing a sieve, as noted in the CAWST Biosand filter Training manual (2009). The process starts with the erection of the wooden frame, then the wire mesh is mounted onto the wooden frame. The process must be repeated four times for sieves of size 0.15 mm, 0.95 mm, 3 mm, and 5-8 mm. An important element to consider when constructing a sieve is the availability of staples. If staples are not available, then nails need to be used. They are used to mount the wire mesh on to the wooden frame.

The BSFZ value chain was designed to be practical and simple enough for the populace of Makwane Village in particular, and other rural African villages, to take over the responsibility of managing all end to end processes. The long term feasibility of such an undertaking will be explored later in the chapter.

### 4.3.3 Manufacturing the SIPP System

Manufacturing the Silver Impregnated Porous pot (SIPP) was a slightly more complex process to execute than that of the BSFZ. The core process of the SIPP system build was the construction of the clay pot. This unique filter element, which studies have shown to be very efficient at cleaning impure water, must be constructed with precision and care in order for it to be effective. There were 21 activities that must be executed in order to efficiently construct the SIPP, making sure that it is effective in its operations. Figure 4.11, in appendix B, depicts the sequence of activities used for the construction of the SIPP system. There are four swim lanes that represent the different objectives that were pursued in order to construct the SIPP. The initial activities were directed toward the clay pot construction process. This is where silver nitrate, sawdust, paper fibre, and ball clay are mixed together to make a clay pot, as depicted in figure 4.12. The clay pot was placed in the sun for drying purposes, The pot was placed in the sun for a total of 36 hours. At this point, care was taken to identify and close all cracks that developed due to the pot’s exposure to the sun.

*Figure 4.12: The clay pot filter element used in the SIPP system*

Source: Momba et al., 2010

After exposure to the sun, the clay pot was placed in an industrial oven furnace and exposed to a precise heating schedule. An industrial furnace oven is not always available for use, especially when one considers that one of the goals of this exercise is for the rural populace to take over the management and execution of all processes involved in the construction and operation of the SIPP. The community cannot afford to purchase an industrial oven, furthermore, the operation and maintenance of this equipment requires the finances and skills that are out of scope for this community.

An alternative to an industrial oven, is the kiln. A kiln is an insulated chamber, which produces temperatures sufficiently high enough to complete processes, such as hardening or drying. In the case of pottery, after materials are shaped and dried, they are fired in a kiln. There are various types of kilns that can be built, for the purposes of this study the focus was on the Roman Kiln as this was the most practical of all kilns that were assessed, and is also easy to construct (Figure 4.13 and figure 4.26 in Appendix B). The construction of a Roman kiln begins with digging tow pits of approximately 50 centimeters apart and each must be 50cm in depth, one pit must be oval shaped, and the other circular. A trench is dug in between the two pits that acts as a stoke hole. The circular pit and the stokehole are lined with pre-fired brick, a slip is used as a mortar to hold the bricks together. After the kiln is built, the dried pots are loaded on top (figure 4.14) and covered in sand. A fire is then lit in the stoke hole. A pyrometer can be used to gauge when the kiln is up to the required temperature.

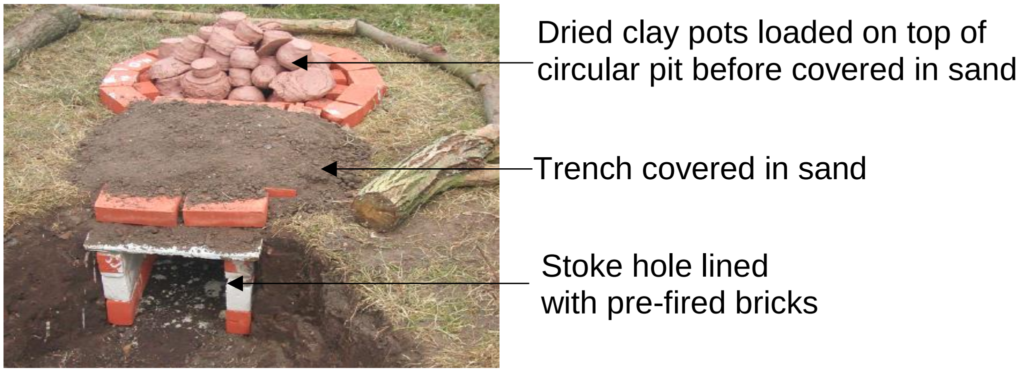


*Figure 4.13: Loading of the clay pots on top of kiln*

Source: Suffolk City Council

*Figure 4.14: Roman Kiln in operation with clay pots*

*Covered in sand on top*

Source: Suffolk City Council

There are numerous types of kilns that can be constructed apart from the Roman Kiln depicted above The roman kiln is specifically constructed for smaller clay pots. Larger clay pots need larger Kilns, such as the one in figure 4.15.

*Figure 4.15: Kiln Constructed for Larger Clay Pots*

*Source: Potter for Peace, 2007*

After the firing process, the clay pot is left to cool down before the final assembly. The final assembly involves fitting the clay pot into the receptacle, which is then fitted into a collection bucket. The base of the 10 litre bucket (the receptacle) is cut in a circular shape, the size of which must be big enough for the clay pot to fit snuggly (figure 4.16 and 4.17). The top of the collection bucket is also cut into a circular shape big enough to fit the receptacle. The collection bucket must be fitted with a spigot to facilitate the collection and use of the clean, filtered water. After assembly, water is poured into the clay pot and left to soak overnight. To commence filter operations, untreated water is poured into the receptacle; it takes approximately one to three hours for the clay pot to filter the unclean water. The filtered water is collected in the collection bucket, as depicted in figure 4.18. The SIPP system must be cleaned regularly to ensure efficient operation. The clay pot must be removed from the receptacle and scrubbed inside with a brush, and rinsed with clean water. The receptacle, collection bucket, and spigot must be cleaned on a weekly basis with soapy or chlorinated water to prevent recontamination. Chlorinated water or any other form of disinfectant must not be added directly into the clay pot as this prevents the efficient function of the filter system.

*Figure 4.16: Clay pot after being placed in a SIPP receptacle*

*Source: Momba et al, 2010*

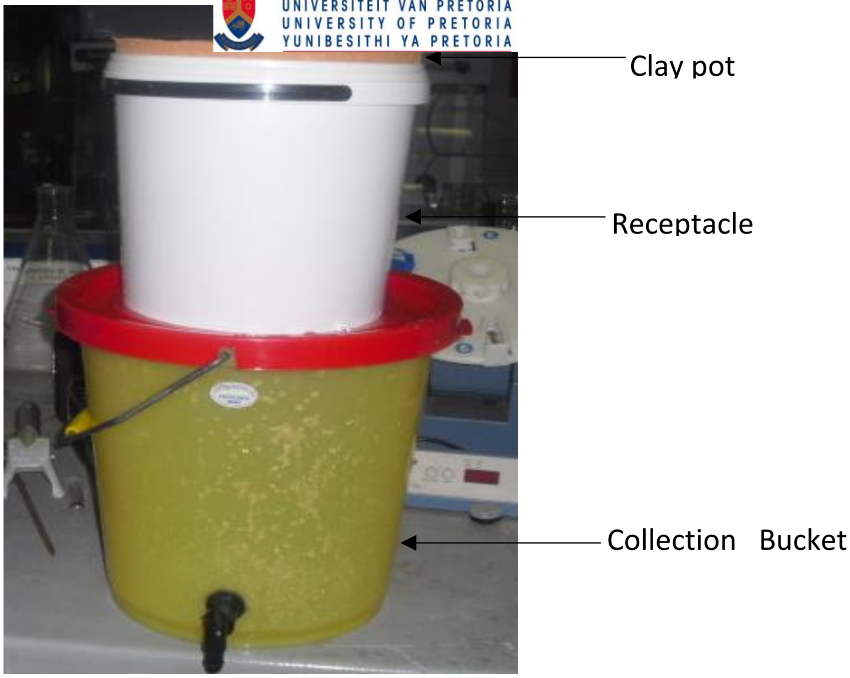


*Figure 4.17: SIPP after final assembly. Source: Momba et al, 2010*

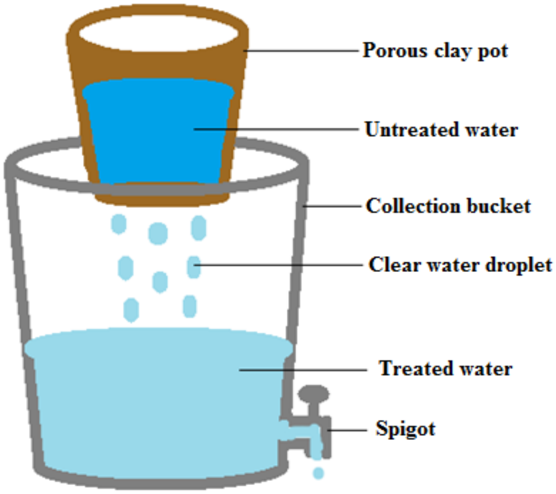


*Figure 4.18: Schematic diagram of the SIPP*

Source: Momba et al., 2010

The efficiency of the SIPP system in removing bacteria from water is well documented. The SIPP consistently produced high quality water that had no presence of indicator bacteria after treatment (Momba et al., 2010; Mwabi et al., 2012). The properties of the SIPP system afford the Makwane community the ability to manage all operations within the value chain. Further, due to the efficacy the system has in removing harmful bacteria, it provides an opportunity to produce and distribute the product to other markets.

### 4.3.4 Outbound Supply and Deployment of the SIPP and BSFZ

The deployment of both the SIPP and the BSFZ systems followed similar processes. The outbound supply and deployment of the SIPP and BSFZ system is depicted in figure 4.19, in appendix B. This phase involves the selection of the packaging for both treatment systems, selection of the type of transportation, and then transporting both systems to the end user.

After an in depth analysis of the packaging options available for both treatment systems, three options were identified due to their low cost and the relative safety provided to the treatment system units during travel. The first packaging option was to place each unit of the treatment system into a cardboard box and wrap the spigot separately in bubble wrap. The second option was to wrap the entire product with bubble wrap, and the third option was to place the entire product into a cardboard box filled with polystyrene balls. All three packaging options had been analysed the results of this analysis will be detailed in the feasibility studies of section 4.4.

The analysis of transportation types was conducted using a number of metrics. The metrics included: the number of products per delivery, conditions on the road, distance covered to end customer, cost of transport mode, and risk of transportation. A decision matrix was then developed to facilitate the selection of the best outbound carrier. Three options were identified during this phase of the analysis. The first option was the renting of two three-ton trucks from AVIS Car Hire for one day. The second option was to hire one eight ton truck rented from Avis for one day. The third option was to hire one eight ton truck rented from Book-a-bakkie for one day. As an added option, a bakkie owned by one of the Makwane residents can be used to pick-up the treatment system units from the production area, and deploy them at Makwane village. This would also add additional value, especially when all processes in the value chain are managed by residents of the village. The detailed analysis of selection of transportation types is presented in section 4.4. After the analysis of the transportation types, all units are loaded into the selected mode of transport, and transported to Makwane village.

Analysis was also conducted on the manner in which units would be distributed once they arrive at Makwane. Details of this will follow.

### 4.3.5 Design and Construction of the Borehole System

Borehole design and development was used as an alternative option to the deployment of the BSFZ and SIPP treatment systems in Makwane village. Borehole construction was seen as more of a potential long term substitute to the SIPP and the BSFZ systems. Therefore, its feasibility in the long term must be analysed to determine if it is a viable alternative to both the BSFZ and the SIPP. Borehole development and construction has five distinct phases. They are area research, hydro census, borehole siting, borehole development, and borehole testing (Figure 4.20 in Appendix B).

The area research involved a literature review of the landscape of the area in which the borehole was to be constructed. The issues addressed in this analysis, involved the number of people currently residing in the area, the demographics of the area including economic activities, and the concerns regarding water in the area. The analysis takes the form of desktop research, where various databases are perused to find information regarding the highlighted topics.

After the desktop research is completed, the next phase requires that a detailed, field work analysis of the area, where a borehole is to be constructed, be conducted. This phase involves determining the economic activities of the selected area, as well as the number of boreholes constructed in the area to date. This is done in order to get a preliminary understanding of the aquifers in the area from those that have built boreholes in the area.

The next phase is the borehole siting. In this phase, a geological, geophysical, and hydro-geological survey of the area is conducted. The outcomes of the analysis are presented together in the form of a groundwater assessment of a particular geographical area (Department of Public Works, 2012). The geological survey is a structural analysis that examines the various types of rock that exist within a particular geography. It indicates, among other factors, the potential presence of subsurface water. It involves drilling into the ground and to determining the type of rocks below ground. Computer programs are used to calculate resource estimates below the ground surface, including the potential amounts of water available. However, assessment results are controlled by geology-based input parameters supplied by knowledgeable assessment geologists and SMEs, as opposed to computer-generated projections of historical statistical trends (Kearey et al., 2002).

Hydrogeological surveys seek to give guidance concerning ground water activity, trends, quality, potential yield, extraction strength, recharge rate, flow direction, and local uses of water within a particular geographical area (Owen, 2011). These surveys identify aquifer systems, of which there are various available. For example, porous aquifers store and spread water through pore spaces between discrete sediment granules. Fractured rock aquifers, on the other hand, store and spread water through crevices, joints, and fractures in impervious rocks. In hydrogeological systems of this type, the speed of groundwater flow is usually much higher than in porous media, although yields are typically low due to restricted groundwater volumes and sporadic recharge events (Owen, 2011). South Africa, Limpopo in particular, shares the same sedimentary basin with Botswana, Zimbabwe and Mozambique. The central parts of the Basin in South Africa and Zimbabwe consist of mostly crystalline rocks and fractured aquifers which have a low ground water potential (Owen and Madari, 2010). This is the basin where Makwane village is situated.

Geophysical surveys gather more information related to subsurface features, such as burials on land, shipwrecks underwater, or the presence of water resources. Archaeologists often use the information they collect to detect and map subsurface features without pursuing destructive or unproductive excavations. Sensors are used to collect subsurface information. Geophysical surveying, although sometimes subject to uncertainties in interpretation, delivers a relatively quick and cost-effective method of deriving information on subsurface geology and the resources potentially available, including the availability of potable water (Kearey et al., 2002).

Borehole development is the commencement of drilling activities to form the borehole. It is a specialized skill and requires that the drill contractor be registered with the Water Association of South Africa. The drilling contract with a contractor is usually based on the meters drilled per hour. It also requires the skills of hydro-geologists and geologists for soil analysis as the drilling occurs. Borehole lengths in South Africa are usually between five to 100 meters, the closer to a river the shallower the borehole. Depending on the length of the borehole, it may take three to seven days to drill a borehole. A structural analysis of the borehole is conducted during the drilling. The structural analysis determines the integrity of a borehole, including the casing necessary to stop the borehole from collapsing.

The final phase of borehole construction, is the borehole testing. The activities pursued in this phase include pump tests, testing for aquifer properties, determining the yield of the water, chemical analysis of water, and the analysis of the water for domestic and agricultural use. A hydraulic engineer designs the pumps, pipes, and tanks required for the implementation and commission of the borehole. Once the construction is complete, the management of the borehole is usually handed over to the local community or the municipality. The municipality is also responsible for maintenance activities, such as replacing valves and pumps, and ensuring that the borehole housing functions optimally. The borehole operator can usually be appointed from the community and trained to operate the borehole.

Borehole construction requires specialized skills that are outside the capacity of the community members of Makwane Village. Though it is a convenient method of providing water to communities it is often expensive to construct and maintain, and only makes sense when the community is large and not scattered, unlike Makwane Village. This situation is also common for most rural African villages. We will expand further on the viability of constructing a borehole for Makwane Village in the following section.

## 4.4 Feasibility Studies

### 4.4.1 Risk Study

A prominent criteria that drives the performance of the HTWS deployment value chain of HWTS, is product risk. An unreliable final product does not provide value to the final consumer, therefore, it was essential to identify the potential causes of product breakdown, and document both its effects and advise how it could be repaired. The (FMEA) model was best suited to analyse and document product risk.

The FMEA model is a methodical technique where potential failures of a product, or process design, are identified, analysed, and documented (Burgess, 1984). Once potential failures have been identified, its effects on product performance and safety are analysed, and suitable actions are taken to eliminate or minimise the effects of these failures. An FMEA is a critical risk tool that aids to avoid costs that are suffered from product failure (Burgess, 1984).

The FMEA process is a continuous, bottom-up methodology, normally employed in the areas of product design, process, and service (Burgess, 1984). A design FMEA scrutinises potential product failures, and the effects of these failures on the consumer. A process FMEA scrutinises the inputs that can affect the quality of a process. A service FMEA is used to prevent the misuse or misrepresentation of the tools and materials used in servicing a product (Burgess, 1984). For the purposes of this study, we will be using the design FMEA, as we would like to create a view of how failures in the performance of the HWTS can potentially affect the end user.

There is no solitary method for conducting a FMEA, though the automotive industry and the U.S. Department of Defence (Mil-Std-1629A) have standardised FMEA procedures within their respective industries. The fundamental features of the FMEA include (Burgess, 1984):

- The failure mode describes the way in which a design fails to perform according to specification.

- The effect describes the impact on the customer resulting from the failure mode.
- The cause(s) describes the means by which an element of the design caused a failure in the performance of a product.

*Table 4.7: The Failure Mode and effects Analysis FMEA of the BSFZ System*

| Process Name | Potential Failure Mode | Potential Effect of Failure | Potential Cause of Failure | $S_o$ (probability of occurence) | $S_d$ (probability of detection) | S (severity of the effect on customer) | RPN (measure of risk) | Recommended Actions |
|---|---|---|---|---|---|---|---|---|
| **Operations of BSFZ** | 1. Low flow rate | Not enough water available when required | Blockage in the plumbing/ Plumbing not well constructed. | 4 | 4 | 6 | **96** | Conduct regular maintenance of the plumbing system. Test that the plumbing system operates correctly when it is first constructed |
| | | | Fine sand moves to lower levels and blocks the filtration process. | 4 | 4 | 6 | **96** | Ensure that the filtration sand is packed according to regulations. Regular maintenance of the filtration sand is crucial to its efficacy in removing pathogens in water |
| | 2. Very high flow rate | Unclean water (not enough time given to filter water) | Sand packed too thinly. Sand not packed according to | 3 | 4 | 6 | **72** | Ensure that the filtration sand is packed according to regulations |
| | | | Undeveloped biological layer | 3 | 4 | 7 | **84** | Ensure that enough time is given (30 days) for the growth of the biological layer |
| | 3. Unclean filtered water | Disease, sickness potential death | Undeveloped biological layer | 3 | 4 | 7 | **84** | Ensure that enough time is given (30 days) for the growth of the biological layer |
| | | | Coarse sand flows into the zeolite level and causes the zeolites to be ineffective. | 4 | 4 | 7 | **112** | Ensure that all filtration sand is packed according to regulations to prevent mixing |
| | | | Poor maintenance of bucket | 4 | 4 | 6 | **96** | Clean the bucket regularly. Ensure the bucket is housed in a cool and clean area |
| | 4. Water Leakage | Mixing of clean and unclean water/ Loss of clean water | Broken plumbing | 4 | 4 | 7 | **112** | Ensure that the plumbing is correctly implemented and operated. |
| | | | Poor maintenance | 4 | 4 | 7 | **112** | Conduct regular maintenbace of the BSFZ system by clean ning the bucket and replacing the top layer of sand |

*Table 4.8: The Failure Mode and effects Analysis FMEA of the SIPP System*

| Process Name | Potential Failure Mode | Potential Effect of Failure | Potential Cause of Failure | So (Probability of Occurence) | Sd (Probability of detection) | S (severity of the effect on customer) | RPN (measure of risk) | Recommended Actions |
|---|---|---|---|---|---|---|---|---|
| **Operations of SIPP** | 1. Low flow rate | Not enough water available when required | Firing/heating of clay pot at incorrect temparature | 6 | 6 | 6 | 216 | Clay pot must be fired at correct temparature to ensure efficacy. A pyrometer will helpto determine when the |
| | | | Incorrect mixing of clay pot ingredients (clay, silver, saw dust) | 6 | 5 | 7 | 210 | Clay, silver and saw dust must be mixed in the correct ratios |
| | | | Use of incorrect equipment to heat clay pot | 6 | 5 | 6 | 180 | Clay pot should only be fired/heated in an industrial oven or kiln |
| | | | Blockage in the plumbing | 4 | 4 | 7 | 112 | Regular use of filter system will reduce blockage. Enusre that plumbing system is implemented correctly |
| | 2. High Flow rate | Unclean water (not enough time given to filter water) | Firing/heating of clay pot at incorrect temparture | 6 | 6 | 6 | 216 | Clay pot must be fired at correct temparature to ensure efficacy. A pyrometer will helpto determine when the |
| | | | Incorrect mixing of clay pot ingredients (clay, silver, saw dust) | 6 | 5 | 7 | 210 | Clay, silver and saw dust must be mixed in the correct ratios |
| | | | Use of incorrect equipment to heat clay pot | 6 | 5 | 6 | 180 | Clay pot should only be fired/heated in an industrial oven or kiln |
| | 3. Unclean filtered water | Disease, sickness potential death | Firing/heating of clay pot at incorrect temparture | 5 | 6 | 7 | 210 | Clay pot must be fired at correct temparature to ensure efficacy. A pyrometer will helpto determine when the |
| | | | Incorrect mixing of clay pot ingredients (clay, silver, saw dust) | 6 | 5 | 7 | 210 | Clay, silver and saw dust must be mixed in the correct ratios |
| | | | Use of incorrect equipment to heat clay pot | 6 | 5 | 6 | 180 | Clay pot should only be fired/heated in an industrial oven or kiln |
| | | | Unclean receptacle/collection bucket | 6 | 4 | 7 | 168 | Clean the receptacle and bucket regularly. Ensure the bucket is housed in a cool and clean area |
| | 4. Water Leakage | Loss of clean water | Broken plumbing | 4 | 4 | 7 | 112 | Regular use of filter system will reduce blockage. Enusre that plumbing system is implemented correctly |
| | | | Poor maintenance of receptacle/collection bucket | 4 | 3 | 7 | 84 | Conduct regular maintenbace of the SIPP system by cleaning the bucket, receptacle and clay pot regulary |

Table 4.7 and 4.8 depict the design FMEA conducted by the author together with the BSFZ and SIPP design team to identify potential failure points from the view of the end user. The FMEA was conducted after continuous testing of both products. Four potential failure modes were identified for both the BSFZ and SIPP. The four modes of failure were the same for both products. Owing to the fact that both products are modified filtration systems, this tended to exhibit the same failure modes that current filtration systems face. The four failure modes were low flow rate; very high flow rate; unclean filtered water; and water leakage.

A flowrate below 150L/day for the BSFZ system was considered a low flow rate (Momba et al. 2013). The low flow rate of the BSFZ, according to the FMEA, can be attributed to blockage in the plumbing. Alternatively, it can also be attributed to the fine sand which sits on the top level of the filter bucket moving down into the lower levels, thus blocking the filtration process.

A low flow rate from the SIPP was determined to be due to four causes, they are: firing/heating of clay pot at an incorrect temperature; incorrect mixing of clay pot ingredients (clay, silver, and saw dust); the use of incorrect equipment to heat clay pot; blockage in the plumbing. The causes of most failure modes of the SIPP system were attributed to the incorrect manufacturing of the clay pot. Care must be taken during this phase as it plays a major part in the efficacy of the SIPP system. The effect of a low flow rate for both the SIPP and BSFZ is that the end user will not have enough water available when required.

The second failure mode for the BSFZ and SIPP system was an abnormally high flow rate. For the BSFZ, the causes of a high flow rate were: sand packed too thinly (sand not packed according to regulations); and an undeveloped biological layer. When sand is packed too thinly in the filter bucket, it doesn’t give enough time for the filtration process to work efficiently, the unclean water is filtered too quickly. The biological layer is essential to the efficient filtration of water, if it is not given the time to develop, the filtration process will be flawed, resulting in unclean filtered water.

Similar to the causes for a low flow rate for the SIPP system, a high flow rate was caused by: firing/heating of clay pot at an incorrect temperature; incorrect mixing of clay pot ingredients (clay, silver, and saw dust); the use of incorrect equipment to heat clay pot; blockage in the plumbing.

A steady/recommended flow rate from the BSFZ may still result in unclean filtered water produced for the end user. This was due to an undeveloped biological layer; the mixing of the filtration sand with the zeolite layer; or the poor maintenance of the filtration bucket. When the sand mixes with the zeolite layer, it renders the zeolites ineffective in removing pathogens from the unclean water. Poor maintenance of the filtration system reduces the efficacy of the BSFZ system to produce clean water.

An incorrectly manufactured clay pot was the main reason why the SIPP system may have produced unclean water. Added to this, a poorly maintained receptacle will also reduce the ability of the system to produce clean water. A lack of clean water for the end consumer will expose them to diseases such as diarrhoea and cholera, thus elevating the mortality rate, especially among the children in the community.

Water leakage in both the SIPP and BSFZ system is caused by poor system maintenance and/or a broken plumbing system. The effect of water leaks from both systems is the loss of clean filtered water.

Once the failure mode, and its effects and causes have been analysed and documented, the risk priority number (RPN) is calculated in order to prioritise the most important potential causes of failure, and the resultant preventative actions that should be taken for each failure mode. The RPN is calculated for each potential cause of failure by multiplying the numerical ratings of the probability of occurrence ($S_O$), and the probability of detection ($S_D$), and the severity of the effect (S) on the end customer ($RPN=S_D \times S_O \times S$)(Carlson, 2012). The failure modes that have the highest RPN should be prioritised for corrective action.

The numerical ratings of the FMEA model presented in this study, used the suggested evaluation criteria presented by Carlson (2012), this is depicted in table 4.9. The rank given to a probability of occurrence, the probability of detection, or the severity of the effect it has on consumers, often depends on the relative novelty of the design or technology. The more original the technology, the higher the chance that it will fail during operations, and therefore, the higher the rank (Carlson, 2012). In the case of the HWTS, most of the technology was similar in design to what was already out on the market. Most input material for the SIPP and BSFZ can be found off-the-shelf, while the technology and materials used to design and operate borehole systems have been well tested under various conditions, thus making them quite robust. Therefore, according to table 4.9, the likelihood of failure of these HWTS products is on the moderate to very low levels.

Concerning the BSFZ, the potential causes of failure that have the highest RPN included: broken plumbing, poor maintenance, and coarse sand flowing into the zeolite level causing the zeolites to be ineffective. For the SIPP system, the potential causes of failure with the highest RPN included: firing/heating of clay pot at incorrect temperature; incorrect mixing of clay pot ingredients (clay, silver, saw dust); use of incorrect equipment to heat clay pot. For every potential cause of failure, the FMEA recommended actions to help reduce the risk of failure.

Corrective action aimed at reducing the risk of failure is the most critical aspect of an FMEA. The FMEA should be studied to decide where corrective action should be taken, including what activities should be taken and when. Concerning both the BSFZ and SIPP, the corrective actions mostly revolve around the regular maintenance of both HWTS systems. Further, when manufacturing both systems, it is important that all instructions stipulated are adhered to in the strictest of terms. This ensures that all product risk issues are minimized or eliminated.

*Table 4.9: Suggested FMEA Occurrence Evaluation Criteria*

| Likelihood of Failure | Criteria: Occurrence of Cause (Design Life/Risk of Item) | Rank |
|---|---|---|
| **Very High** | New Technology/New design no history. | 10 |
| **High** | Failure is inevitable with new design, new application, or change in duty cycle/operating conditions. | 9 |
| | Failure is likely with new design, new application or change in duty cycle/operating conditions. | 8 |
| | Failure is uncertain with new design, new application, or change in duty cycle/operating conditions | 7 |
| **Moderate** | Frequent failure associated with similar designs or in design simulation and testing. | 6 |
| | Occasional failures associated with similar designs or in design simulation and testing. | 5 |
| | Isolated failures associated with similar design or in design simulation and testing. | 4 |
| **Low** | Only isolated failures associated with almost identical design or in design simulation and testing. | 3 |
| | No observed failures associated with almost identical design or in design simulation and testing. | 2 |
| **Very Low** | Failure is eliminated through preventative control. | 1 |

***Source: Carlson, 2012***

The criteria used to measure risk in this study, was the RPN which is an indication of the design life of an item. The efficient and reliable operation of a borehole is dependent on whether the correct processes were followed to identify, analyse and develop it. Reliable borehole operations are also dependent on structured maintenance activities. Borehole and pump maintenance is important in order to realize the best return on this investment. Therefore, it is recommended to always use a Borehole Water Association (BWA) approved contractor when investing in a borehole. The BWA stamp of approval ensures that contractors use the correct construction and maintenance methods. The maintenance activities of a borehole are usually allocated to the local municipality, often these activities are not executed and the borehole becomes obsolete. This is one of the negative sides of constructing a borehole in a rural area. Provided that an approved contractor is used to construct the borehole and there is a maintenance plan in place, decision makers have allocated the borehole an RPN of 90.

### 4.4.3 Social Impact and Accessibility Study

There were two aspects to the social impact study. The first is a brief review of the difficulties currently suffered by the residents of Makwane Village with regard to water collection. The second part of the study analysed how the deployment of the SIPP and the BSFZ affects the socio-economic environment of the residents of Makwane Village. In particular, analysis was conducted regarding how Makwane residents can be included in the operations and management of the HWTS value chain, and the skills required to do so efficiently. We also determined whether these newly learned skills were applicable to the current job market in South Africa.

*Table 4.12: Accessibility to Water Sources in Makwane Village*

| | |
|---|---|
| Average return distance to water source | 373 (m) |
| Maximum return distance to water source | 2000 (m) |
| Minimum return distance to water source | 1 (m) |
| Average time taken to collect water (minutes) | 22 (min) |
| Longest time to water source and return (minutes) | 40 min |
| Shortest time to water source and return (minutes) | 1 min |

Table 4.12 above depicts the distances travelled and the time it takes residents of Makwane Village to collect water. The Makwane community spent an inordinate amount of time and effort to collect water, especially when considering that the water collected was often not fit for consumption as it was a fertile ground for the development waterborne diseases (Mahlangu, 2012). Almost all Makwane households did not have indoor plumbing; residents walked an average of 373 meters (return) to collect water at a nearby river which took an average of 22 minutes. The scattered composition of the community meant that some households were closer to water sources than others, with distances as far as 1km (2 km return) travelled to collect water. The consumption of impure water prevented capable residents from directly participating in economic activities, while waterborne diseases, like diarrhoea is the greatest killer of children under the age of 5. Though the deployment of HWTS will do little to reduce the distances travelled by residents to collect water, it will play a major role in eliminating pathogens in the water, thus reducing sickness and death. This allows residents to be able to play a greater role

in the economy and play a part in alleviating poverty. It is this social economic value to the HWTS deployment value chain that we wish to uncover.

In order to involve the residents of Makwane Village in the HWTS supply chain, it was necessary to analyse both the sourcing and manufacturing practices used to produce the SIPP and BSFZ. During the initial production of the SIPP and BSFZ, all input materials were sourced from companies within the Tshwane/Pretoria, and Johannesburg metropolitan areas, while manufacturing occurred in Pretoria. Most of the residents in Makwane Village had no access to transportation, or lacked the necessary funds to acquire transportation. This matter becomes more relevant when seeking to include Makwane Village residents in the operations of HWTS deployment value chains. If the SIPP or BSFZ were to be manufactured in Makwane village with the same suppliers, these suppliers would be between distances of 250 to 320 km from the manufacturing site in Makwane. The costs of sourcing input materials would be enough to severely impact the sustainability of the value chain.

*Table 4.13: Materials sourced for the Manufacture of the BSFZ*

| **Item** | **Quantity** | **Current Suppliers** | **Distance from Supplier to Makwane Village (km)** |
|---|---|---|---|
| 25 l bucket | 120 | Plastilon (Six fountains, Pretoria) | 10 |
| Spigot | 120 | Builders Warehouse (Woodlands, Pretoria) | 10 |
| Clear tubing | 120 m | Builders Warehouse (Woodlands, Pretoria) | 10 |
| Insert elbow (90°, 20 mm) | 120 | Builders Warehouse (Woodlands, Pretoria) | 10 |
| Insert male elbow (90°, 20 mm) | 120 | Builders Warehouse (Woodlands, Pretoria) | 10 |
| Thread tape | 120 | Builders Warehouse (Woodlands, Pretoria) | 10 |
| Fine sand (0.075 - 0.3 mm) | 40 kg | Rolfes Silica (Old Rustenburg Road, Brits) | 10 |
| Coarse sand (0.6-1.5 mm) | 40 kg | Rolfes Silica (Old Rustenburg Road, Brits) | 10 |
| Gravel (4-9 mm) | 40 kg | Rolfes Silica (Old Rustenburg Road, Brits) | 10 |
| Zeolites (3 mm) | 50 kg | Pratley (Krugersdorp) | 400 |

Table 4.13 and 4.14 represent the proposed new suppliers of the material inputs for the BSFZ and the SIPP if the manufacturing site was moved from the CSIR in Pretoria, to Makwane Village. The maximum distance a resident would travel is 76km, the distance from Makwane to Middelburg, which is the main town in the area. An exception lies with the sourcing of zeolites for the BSFZ from Pratley, which is based approximately 400 km away in Krugersdorp.

Pratley was the only source for the zeolites used in the construction of the BSFZ. An Alternative to Pratley would be the use of Plusten Distributors. Plusten are a distribution company specialising in the delivery of industrial products, including Zeolites (www.plusten.co.za). Plusten Distributors are capable of delivering goods directly to Roosenekal, approximately 10km outside of Makwane Village. Similarly, in the case of the SIPP, Sigma Aldrich, who are the providers of Silver granules ($AgNO_3$) and other chemical products, have headquarters in Kempton Park, outside Johannesburg, but can deliver products to Roosenekal (www.sigmaaldrich.com). The costs of sourcing input materials will be discussed in detail in the cost assessment to follow.

*Table 4.14: Current Status of Materials, and Suppliers Required for the Manufacture of the SIPP at Makwane*

| **Item** | **Quantity** | **Proposed Suppliers** | **Distance from Makwane (km)** |
|---|---|---|---|
| 20 l bucket | 120 | Roosenekal | 10 |
| 10 l bucket | 120 | Roosenekal | 10 |
| Silver granules ($AgNO_3$ > 99%) | 30 kg | Sigma-Aldrich (Kempton Park/Roosenekal) | 247 /10 |
| Ball Clay | 40 kg | Corobrick (middleburg) | 76 |
| Saw dust | 25 kg | Beaver Saw dust Suppliers (Middelburg) | 76 |
| Paper fibre | 40 kg | R&F Paper Mills, Middelburg | 76 |
| Spigot | 120 | Roosenekal | 10 |
| Clear tubing | 120 m | Roosenekal | 10 |
| Insert elbow (90°, 20 mm) | 120 | Roosenekal | 10 |
| Insert male elbow (90°, 20 mm) | 120 | Roosenekal | 10 |
| Thread tape | 120 | Roosenekal | 10 |

If the proposed new suppliers replace the current ones in the HWTS value chain, it is permissible to conclude that Makwane residents could play a greater part in the operations and management of the value chain. The furthest residents have to travel to procure input materials is Middelburg. This town is familiar with residents as they often take trips there for activities such as shopping. The costs associated with the procurement of parts, and its potential benefits, will be discussed in details in the sections to follow.

The manufacturing of both the SIPP and BSFZ, as depicted in Appendix B, was a profoundly manual process which necessitated the need for a semi-skilled human work force. Makwane residents are perfectly placed to take over the manufacturing of both products, provided that they are equipped with the right tools and knowledge. In light of this, special workshops have been held in Pretoria at the Tshwane University of Technology (TUT), where selected Makwane residents were trained on the manufacturing process of both the BSFZ and the SIPP.

The transfer of skills that occurred during the training can be used by residents, to not only play an active part in the deployment of the HWTS value chain, but could also, potentially, act as a catalyst for them to actively participate in the economy. The skills transferred to residents could allow them to search for jobs that they were previously not eligible for. In order to further investigate this, we asked relevant authorities and SMEs at the (TUT) whether the skills learnt by the selected Makwane residents was enough to make them eligible for jobs in the formal economy. The response was that there is a need for artisans in the South African market, provided that these artisans received their skills from an accredited institution. This would be the signal required by potential employers, to let them know that these individuals had the requisite skills necessary to execute work.

### 4.4.4 Product Effectiveness

*Table 4.15: Microbial removal performance of the BSFZ and the SIPP*

| **HWTS** | **Microbial removal (%)** | | | **Turbidity Removal (%)** | **Water production (L/ day)** | **Comments** |
|---|---|---|---|---|---|---|
| | Bacteria | Viruses | Protozoan parasites | | | |
| BSF-Z | 90-100 | 80.5-100 | 92-95.75 | 12-97 | >150 | The BSFZ has higher flow if 3 mm zeolites used, though the Zeolite layer may need to be replaced periodically. |
| SIPP | 100 | 90.6-100 | 96-99.15 | 59- 99 | 10-20 | The SIPP has a long filter life if it remains unbroken. The filter has low flow rates (1-4 ℓ /h) even for low turbidity waters |

***Source: Momba et al., 2013***

Table 4.15 depicts the result of a study conducted by Momba et al. (2013). The study sought to determine the ability of HWTS, particularly the BSFZ and the SIPP, to effectively remove pathogens in water. The study also determined the flow rate of both HWTSs. The results show that the SIPP is more effective in microbial and turbidity removal when compared to the BSFZ. The BSFZ has a much higher flow rate of 150 litres per day, this is on par with the recommendations of the SANS. It was also noted that the SIPP has a longer filter life compared to the BSFZ; this is because the zeolites in the BSFZ requires regular maintenance.

It is generally thought that borehole water requires little purification. This is due to the fact that it is located deep underground and is generally bereft of impurities (Momba et al., 2013). This situation is also true for Makwane Village, where previous boreholes have required no further treatment before consumption. Depending on the pump system used to extract the water, the borehole can easily produce the recommended 150 litres per day

### 4.4.5 Cost/Financial Study

The overall viability of deploying water treatment systems at Makwane largely depends on the supply chain costs. The costs undertaken to deploy the SIPP and

BSFZ at Makwane Village were determined by analysing the sourcing, manufacturing, and delivery components of the supply chain for each treatment system together as a system, rather than individually. The result of the analysis was then compared with the costs required to construct a borehole system/s in Makwane. The cost analysis of all three systems took into account the involvement of the Makwane community in the supply chain. Specific processes in the supply chain that could be completed by the community were allocated to individuals within Makwane community.

Table 4.16 depicts the cost of materials used to construct the BSFZ, along with the supplier of each input material.  The cost analysis looked at the deployment of 120 units of the BSFZ along with enough parts to construct an additional 20 units per annum.  The cost of materials for the construction of 120 units of the BSFZ was R16 347.78, while it cost R2724.63 for the additional 20 units of the BSFZ.

*Table 4.16: Material Cost per Unit of BSFZ*

| **Item** | **Quantity** | **Supplier** | **Material Unit Cost** | **Material cost per Unit of BSFZ** | **Material Cost for 120 units Of BSFZ** | **Costs Required for additional 20 Units** |
|---|---|---|---|---|---|---|
| 25 l bucket | 1 | Roosenekal Hardware Store | R 25.58 | R 25.58 | R 3 069.60 | R 511.60 |
| Spigot | 1 | Roosenekal Hardware Store | R 49.99 | R 49.99 | R 5 998.80 | R 999.80 |
| Clear tubing | 1 m | Roosenekal Hardware Store | R 24.99 | R 12.50 | R 1 499.40 | R 249.90 |
| Insert elbow (90 °, 20 mm) | 1 | Roosenekal Hardware Store | R 3.79 | R 3.79 | R 454.80 | R 75.80 |
| Insert male elbow (90 °,20 mm) | 1 | Roosenekal Hardware Store | R 3.79 | R 3.79 | R 454.80 | R 75.80 |
| Thread tape | 1 | Roosenekal Hardware Store | R 6.49 | R 6.49 | R 778.80 | R 129.80 |
| fine sand (0.075 - 0.3 mm) | 40 kg | Roosenekal Hardware Store | R 28.00 | R 1.40 | R 168.00 | R 28.00 |
| Coarse sand (0.6-1.5 mm) | 40 kg | Roosenekal Hardware Store | R 30.24 | R 0.76 | R 90.72 | R 15.12 |
| Gravel (4-9 mm) | 40 kg | Roosenekal Hardware Store | R 34.82 | R 0.87 | R 104.46 | R 17.41 |
| Zeolites (3 mm) | 50 kg | Pratley | R 155.35 | R 31.07 | R 3 728.40 | R 621.40 |
| **Total per Unit Cost** | | | | **R 136.24** | **R 16 347.78** | **R 2 724.63** |

Every material required for the production of the BSFZ, excluding the zeolites, can be purchased in Roosenekal, 10km outside Makwane Village. The nearest place to purchase zeolites was Pratley in Krugersdorp. The close proximity of the other suppliers allows the Makwane community to source the required materials for construction. This allows them to be active participants of the water treatment chain.

In order to procure all input materials required to construct 120 units of the BSFZ, with spare parts to construct an additional 20 units, an assumption is made by the author that a truck (bakkie) is required to transport all materials. A 1.4 litre bakkie can be used to collect supplies from the suppliers in Roosenekal and Krugersdorp region. The fuel consumption of such a vehicle is approximately nine litres /100km. Table 4.17 below displays the costs of the inbound transportation processes for the BSFZ. A single round trip from Makwane Village to Roosenekal, Krugersdorp and back to Makwane to pick up all materials required to construct 120 units, will cost R870.48 at a fuel cost of R12.09 per litre.

*Table 4.17: Transportation Costs for the BSFZ*

| **Item** | **Supplier** | **Distance to Makwane (Km)** | **Transportation Method** | **Trip** |
|---|---|---|---|---|
| 25 l bucket | Roosenekal Hardware Store | 10 | Road | R 21.76 |
| Spigot | Roosenekal Hardware Store | 10 | Road | R 21.76 |
| Clear tubing | Roosenekal Hardware Store | 10 | Road | R 21.76 |
| Insert elbow (90°,20 mm) | Roosenekal Hardware Store | 10 | Road | R 21.76 |
| Insert male elbow (90°,20 mm) | Roosenekal Hardware Store | 10 | Road | R 21.76 |
| Thread tape | Roosenekal Hardware Store | 10 | Road | R 21.76 |
| fine sand (0.075 -0.3 mm) | Roosenekal Quarry | 10 | Road | R 21.76 |
| Coarse sand (0.6-1.5 mm) | Roosenekal Quarry | 10 | Road | R 21.76 |
| Gravel (4-9 mm) | Roosenekal Quarry | 10 | Road | R 21.76 |
| Zeolites (3mm) | Pratley (Krugersdorp) | 400 | Road | R 870.48 |
| **Total costs for One Round Trip R 870.48** | | | | |

Makwane Secondary school was identified as a potential staging area for the manufacturing of the BSFZ. The local government absorbs all the utility costs of the school; therefore, it is assumed that all property, electrical, and water costs derived from the manufacturing of the BSFZ units will be absorbed by the local government. Labour costs are calculated for a six man crew working on the manufacturing of 120 units of the BSFZ. The monthly minimum wage for labour, as determined by a private sector bargaining council, is R2 724 (http://www.mywage.co.za/main/salary/minimum-wages/faqs).). Therefore, the cost of labour was R16 390.44 to build the BSFZ units in a month. This excludes the extra R2 724 that was reserved for the labour needed to repair BSFZ units that are already operational, using the spare parts that have been purchased. The spare parts were enough for an additional 20 units, this has been accounted for in the input material costs. Consequently the total labour cost for the construction of the BSFZ units was R21 804.

Table 4.18 below displays the costs of the tools required to construct the BSFZ. If the manufacturing process applies concepts like the division of labour, and uses an assembly line where each of the six labourers are assigned different jobs on the line, following the process steps that were outlined in section 4.3.1.3, there would be no need to purchase more equipment if the demand for the BSFZ was to increase, because the division of labour allows for the six man team to produce more than the required 120 units and repairs. Labour should be divided in accordance with the swim lanes in figure 4.2 of appendix B.

*Table 4.18: Tools Required to Manufacture the BSFZ and SIPP*

| **Item** | **Cost** | **Supplier** |
|---|---|---|
| Power Drill | R 449 | MICA Hardware stores |
| 20 mm hole saw | R 80 | MICA Hardware stores |
| 2 mm drill bit | R 55 | MICA Hardware stores |
| Craft knife | R 120 | MICA Hardware stores |
| Hardware or strong pair of scissors | R 180 | MICA Hardware stores |
| Ruler or measuring tape | R 40 | MICA Hardware stores |
| Pencil or black marker | R 10 | MICA Hardware stores |
| **Total** | **R 934** | |

*Table 4.19: Material Unit Cost for a Single Implementation of the BSFZ*

| **Material Costs** | **Amount** |
|---|---|
| 120 units of BSFZ | R 16 347.78 |
| 20 units (spare parts) for BSFZ | R 2 724.63 |
| **Labour** | |
| Once off | R 16 390.44 |
| Maintenance | R 2 731.74 |
| Equipment | R 934.00 |
| Transportation (inbound) | R 870.48 |
| **Total Implementation Costs** | **R 39 999.07** |

Table 4.19 above summarises the implementation costs of 120 units of the BSFZ, as well as additional spare parts. The table also includes labour costs and inbound transportation costs. It is assumed that the deployment costs will be minimal because the manufacturing occurs within Makwane Village, allowing each household to collect a unit of the BSFZ when it is completed. The total cost of a once off implementation, allowing the BSFZ to be used for a year, is R 39 999.07.

In order to minimise the overall costs associated with the construction of the BSFZ for the Makwane community, it was possible to collect sand and gravel for free from the nearby quarry outside Roosenekal. The sand can be filtered using wire meshes that filter the sand into the different sizes required. Table 4.20 depicts the costs required to construct the three wire meshes required to filter the sand into the three different sizes. It must be stressed that the sand collected from the quarry may not be of the required quality to be efficient in removing pathogens from polluted water. Therefore, all sand that is collected outside of the recommended suppliers must be clean and free of impurities. Collecting sand independently must be viewed as a temporary solution, this author recommends the purchase of good quality sand from the recommended suppliers as it guarantees a good quality final product.

*Table.4.20: Cost of Building Wire Meshes*

| **Materials** | **Cost** | **Supplier** |
|---|---|---|
| 5/7 mm mesh/wire screen | R 52.00 | http://meshforbirds.co.za/ |
| 3 mm wire screen | R 86.00 | http://meshforbirds.co.za/ |
| 0.95/1 mm wire screen | R 46.00 | http://meshforbirds.co.za/ |
| 0.15/0.2 mm wire screen | R 42.00 | http://meshforbirds.co.za/ |
| Nails | R 50.00 | MICA |
| 1.3 cm staples (if available) | R 20.00 | MICA |
| 2.5 cm x 2.5 cm wood strapping | R 45.00 | MICA |
| 2.5 cm x 10 cm wood | Easy to find/Free | None |
| Building equipment | None | None |
| Hammer | R 200.00 | www.ggstore.co.za |
| Saw | R 115.00 | www.ggstore.co.za |
| Tape Measure | Accounted | |
| Labour | Accounted | |
| Overhead | None | |
| **Total** | **R 656.00** | |

Table 4.21 displays the input materials required to construct the SIPP. It costs R 35 415.34 to purchase the input materials for the construction of 120 units of the SIPP. An additional R 5 902.56 is required to purchase enough spare parts to construct 20 additional units. The suppliers of all input materials are situated in the Rossenekal and Middelburg region. Though Sigma Aldrich, the supplier of silver granules, does not have an outlet Near Makwane (They are based in Kempton Park), it is possible for them to deliver at Roossenekal.

*Table 4.21: Material Cost of the SIPP*

| **Item** | **Quantity** | **Supplier** | **Material Cost per Unit of SIPP** | **Cost Required to make 120 Units** | **Costs Required for Additional 20 Units** |
|---|---|---|---|---|---|
| 20 l bucket | 1 | Plastilon | R 22.58 | R 2 709.60 | R 451.60 |
| 10 l bucket | 1 | Plastilon | R 11.48 | R 1 377.60 | R 229.60 |
| Silver granules ($AgNO_3$ > 99%) | 0.25 kg | Sigma-Aldrich | R 160.90 | R 19 687.50 | R 3 281.25 |
| Ball Clay | 40 kg | Corobrik | R 19.08 | R 2 348.80 | R 391.47 |
| Saw dust | 25 kg | Chamberlains | R 0.30 | R 35 | R 5.76 |
| Paper fibre | 40 kg | Sappi, Enstra mill | R 0.59 | R 70.68 | 11.78 |
| Spigot | 1 | Builders warehouse | R 49.99 | R 5 998.80 | R 999.80 |
| Clear tubing | 1 m | Builders warehouse | R 12.50 | R 1 499.40 | R 249.90 |
| Insert elbow (90°,20 mm) | 1 | Builders warehouse | R 3.79 | R 454.80 | R 75.80 |
| Insert male elbow (90°,20 mm) | 1 | Builders warehouse | R 3.79 | R 454.80 | R 75.80 |
| Thread tape | 1 | Builders warehouse | R 6.49 | R 778.80 | R 129.80 |
| **Total Unit Cost** | | | **R 291.49** | **R 35 415.34** | **R 5 902.56** |

*Table 4.22: Inbound Transportation Costs for the SIPP*

| **Item** | **Supplier** | **Distance to Makwane (Km)** | **Transportation method** |
|---|---|---|---|
| 20 l bucket | Roosenekal Hardware Store | 10 | Road |
| 10 l bucket | Roosenekal Hardware Store | 10 | Road |
| Silver granules ($AgNO_3 > 99\%$) | Sigma Aldrich (Roosenekal dropoff) | 10 | Road |
| Ball Clay | Corobrick Middelburg | 70 | Road |
| Saw dust | Woodworx Middelburg | 70 | Road |
| Paper fibre | R&F Paper Mills Middelburg | 70 | Road |
| Spigot | Roosenekal Hardware Store | 10 | Road |
| Clear tubing | Roosenekal Hardware Store | 10 | Road |
| Insert elbow (90 °, 20 mm) | Roosenekal Hardware Store | 10 | Road |
| Insert male elbow (90 °, 20 mm) | Roosenekal Hardware Store | 10 | Road |
| Thread tape | Roosenekal Hardware Store | 10 | Road |

The table 4.22 above displays the costs of the inbound transportation processes for the SIPP. A single round trip from Makwane Village to Roosenekal, Middelburg and back to Makwane to pick up all materials required construct 120 units, will cost R 456 assuming cost of six rands per kilometre (depending on vehicle type). This model assumes that one of the Makwane members will provide their vehicle to be used for transportation. This assumption is valid as it was noted that residents of Makwane village often use the vehicle of one community member to go shopping in Middelburg (the furthest distance travelled for material sourcing)

As with the construction of the BSFZ, this author recommends the use of manufacturing processes that applies the division of labour concept in accordance with the swim lanesswimlanes in section 4.3.1.3. This ensures a quick turnaround in the production of the product while keeping labour costs at a minimum.

Table 4.23 below summarizes the costs of implementing 120 units of the SIPP, as well as additional spare parts for 20 units. The labour costs for the SIPP construction, similar to the BSFZ, are based on the monthly minimum wage for labour as determined by a private sector bargaining council, is R2 724 (http://www.mywage.co.za/main/salary/minimum-wages/faqs).). The total labour cost is projected for a sixman team deploying 120 units in a month, and an additional R2 731R2731.70 left for the labour required to repair defective units.

One of the design recommendations for the Kiln mentioned earlier in the text, is that the clay pot should be  fired, either in an industrial oven or a kiln. The industrial oven requires specialized skills for operation and maintenance, not to mention additional costs such as electricity. Overall, the use of the oven incurs severe overhead costs. This makes it an unnecessary burden for the Makwane community and would make it infeasible to deploy the SIPP in Makwane.

*Table 4.23: Material Unit Cost for a Single Implementation of the SIPP*

| **Material Costs** | |
|---|---|
| 120 units | R 35 415.34 |
| 20 units (spare parts) | R 5 902.56 |
| **Labour** | |
| once off | R 16 390.44 |
| maintenance | R 2 731.74 |
| **Equipment** | R 934 |
| Kiln Construction and Implementation | R 4 991 |
| **Transportation (inbound)** | R 631.10 |
| **Total implementation costs** | **R 66 995.95** |

The use of a kiln, depicted in figures 4.13 - 4.15 has been identified as the preferred alternative to the industrial oven. Table 4.23 summarises the construction costs of the kiln at Makwane.  According to quantity surveyors of Trencon Construction (pty) Ltd, the cost of constructing a kiln at Makwane village is R4 990.78. The operation of the kiln only requires wood to start the fire required to heat up the clay pots.

*Table 4.24: Cost of Construction of a Kiln*

| **Description** | **Unit** | **Cost** | **Delivery** | **Escalation** | **Wastage** | **Amount** |
|---|---|---|---|---|---|---|
| *Structure Dimension: 1500mm x 1500mm x 2500mm* | | | | | | |
| **Material** | | | | | | |
| Building Sand | $m^3$ | R 118.00 | R 100.00 | - | 10.00% | R 239.80 |
| Crusher Dust | ton | R 90.16 | R 100.00 | - | 10.00% | R 209.18 |
| G5 Backfill Material | $m^3$ | R 192.00 | - | - | 25.00% | R 240.00 |
| Stock Bricks | /1000 | R 2 916.00 | 600.00 | - | 5.00% | R 3 691.80 |
| **Labour Component: Based on estimated completion time of 4hours** | | | | | | |
| General Labour : two required | /hour | R 41.25 | - | - | - | R 330.00 |
| Skilled Labour : Brick Layer - one required | /hour | R 70.00 | - | - | - | R 280.00 |
| **Total Estimated Cost** | | | | | | **R 4 990.78** |

Installing a borehole system is the costliest to implement of all the three proposed water treatment systems, as is evidenced by table 4.25. It also required specialised skill to identify the correct drilling areas, drill the borehole, insert a steel casing and pump, and test the yield and the purity of the water. These skills ensure that the water provided to the end user is of the finest quality.

*Table 4.25: Cost of Borehole Construction*

| **Description** | **Net Price** |
|---|---|
| Travelling Cost for Drill | R 850.00 |
| Drill (0-120M @250 P/M) | R 60 000.00 |
| Drill (120-150M @250 P/M) | R 8 850.00 |
| Casing Steel (177 X 3 MM 18M @325 P/M BH2) | R 5 850.00 |
| Casing Steel (177 X 3 MM 6M @325 P/M) | R 1 950.00 |
| **Sub Total** | **R 77 500.00** |
| YIELD TESTING OF BOREHOLE ( 3 HOURS 95 METER 2.2KW PUMP) | R 4 000.00 |
| TESTING OF WATER QUALITY SANS 241 | R 1 940.00 |
| **Total** | **R 83 440.00** |

The local municipality is required to do regular borehole maintenance, such as changing valves/pumps and making sure the borehole housing is correctly fitted. However, regular maintenance activities do not often occur in the rural areas of South Africa. Much of the building equipment installed in Makwane was dilapidated and required maintenance. Installing a borehole system was not the only requirement. Creating an active and skilled maintenance workforce is necessary to ensure the continued efficient activity of the borehole system for a number of years. Furthermore, borehole vandalism is a problem that can render the borehole system unusable. Vandals take pipes, saddles, air heaters, water heaters, and electrical fittings. The costs of maintenance, and eliminating vandalism, make the installation of the borehole system unpredictable. Though vandalism, along with irregular maintenance, are the major drawbacks of installing a borehole system, ensuring that these problems are dealt with makes the installation of a borehole system an attractive choice, but only in the long run.

The adoption of the SIPP and the BSFZ promises the inclusion of the Makwane community into the supply chain. Though this is good news for the community, the hypothesis remains to be tested.  A cost model was designed to determine the long-term viability and ultimate profitability of implementing the SIPP and the BSFZ system in Makwane Village. Sustainability was defined as the point in which the supply chain could absorb all operational costs without the need for external financial injections. This means that procurement, manufacture, and sales of the HWTS would be left in the hands of the Makwane community. The period of analysis was over ten years, all costs, including material, labour and overhead costs was increased by 10% year on year to account for inflation (Table 4.25 – Appendix D). This increased the unit cost of production by 10% year on year. The mark up on cost was set at different levels to determine the point at which the supply chain of the BSFZ and SIPP become sustainable. All relevant tables and figures for this cost study are presented in Appendix D.

The model assumes that all households in Makwane village purchase at least one HWTS system, therefore, 120 units are sold annually with enough spare parts to construct a further 20 units. All costs increase by 10% annually. The model only analyses the situation in Makwane Village exclusively. All profits generated from the sale of HWTS in a year are re-invested into the next year.

Figure 4.21 depicts the annual profit derived from setting the selling price of the BSFZ at 20% on unit cost year on year. Profits increased continually annually from R7 999 in year one to R12 401 in year ten. This was due to the annual 20% percent increase in selling price annually even though unit costs also increased annually. The unit selling price of the BSFZ ranged from R342 in year one to R531 in year ten. Cumulative profits for the ten years stood at R100 460. Though profits derived from the BSFZ supply chain increased annually, there remained a need for an annual external investment in order to produce 120 units of the BSFZ and 20 units of spare parts. This meant, over a period of 10 years, the supply chain was not sustainable at a mark-up of 20% (Figure 4.22).

When the mark-up was set at 30% percent annually on cost, profits continued to increase annually (Figure 4.23). The annual profit in year one stood at R11 999 and increased steadily to R18 651 in year ten. This is a result of the unit selling price of R 371 in year one increasing to R 576 in year ten. Cumulative profits stood at R150 931. Similarly, the annual investment also increased annually, but the increase in investment was less pronounced than it was when the mark-up was set at 20% on cost. The investment in the first year is approximately R40 000. This decreases to below R30 000 in year two but then steadily rises to R44 322 in year ten (4.24).

The mark-up on cost was increased gradually by increments of ten percent until a point was reached where the BSFZ supply chain became sustainable, which meant that no further investment was required for it to continue operating. Figure 4.25 depicts the results of adding an annual 105% mark–up on cost to the BSFZ selling price. At this point, profit margins range between R42 000 in year one to R65 154 in year ten. Figure 4.26 shows that at this mark-up, no investment is required beyond the initial first year investment for the purchase of input materials, labour and equipment. An annual increase in mark-up meant that the selling price of the BSFZ increased from R585 in year one to R908 in year ten. It is questionable whether Makwane residents can afford the BSFZ at these prices.

The cost model of the SIPP follows the same principles as that of the BSFZ. Table 4.26, depicts the cost structure of the SIPP. Similar to the BSFZ cost model, all implementation costs are increased by ten percent annually over a period of ten years.

Figures 4.27 and 4.28 depict the profit and required annual investment into the SIPP supply chain with an annual mark-up on cost of 20%. The unit selling price of the SIPP ranged between R 560 in year one and R1 320 in year ten. This resulted in profits ranging between R11 390 in year one to R26 856 in year ten with cumulative profits of R181 516 for the ten year period. It is immediately noticeable that the costs and selling price of the SIPP are slightly higher than those of the BSFZ.

When the selling price of a unit of the SIPP was set at 30% mark-up on cost, profits ranged between R20 100 for year one and R41 391 for year ten for the sale of 120 units, with a cumulative profit of R320 322 over the ten year analysis period. Annual investment ranged between R66 995.95 (year one) to R114 889 (year ten). The selling price for one unit of the SIPP ranged from R 622 (year one) to R1 466.89 (year ten).

As the mark-up on costs increased, the profit from the sale of 120 units of SIPP increased. This brought about a decrease in the amount of annual investment required to keep the SIPP supply chain to minimal levels. After the initial investment of R66 996 in year one, in the remaining nine years investment ranges between R3 350 in year two and R7 180 in year ten (Figure 4.32). The selling price of the SIPP at this mark-up has a positive influence on the annual re-investment, though the question remains whether the residents of Makwane would be willing to purchase the SIPP at unit selling prices that range between R981 in year one and R2 313 in year ten. Figure 4.33 and 4.34 depicts the annual profit derived from the SIPP value chain when the selling price is set at 110% mark up on cost. At this point there is no need for further investment after the initial investment of R66 996.

## 4.5 Discussion

The supply chains of the three proposed systems have elements that make them similar in some cases, but also individually different. The criteria used to analyse the three supply chains provide a platform from which comparisons between the them can be made.

The process maps of the value chains of the BSFZ and the SIPP systems have a number of similarities, particularly when it comes to some of the input materials required to build the systems. Materials such as the receptacle buckets, insert elbows, thread tape, and the spigots can be accessed from the same vendor. This could allow the production of both systems in a similar setting. The production of both systems in the same setting also creates more value in the treatment system supply chain by allowing the Makwane community to play a central role in the production and distribution of both the SIPP and BSFZ in the geographical area. The potential expanded value in the chain is good news for employment of people within the geographical area.

The selection and implementation of a borehole system ensures regular supply of water, though this comes with some constraints, especially when it comes to incorporating the community into the design, implementation and maintenance of borehole systems.  Boreholes require specialised skills to operate in a good working order, these skills are not available in the Makwane community presently. Further, the frequent theft of equipment such as pumps and valves means that the supply chain of boreholes often suffers from value losses that disrupt the normal functioning of the borehole system. This has a direct effect on water supply within the community, hence the health of the community. Additionally the frequent lack of maintenance reduces the functionality of borehole systems. These problems with the borehole can be fixed with strategic funding to equip and train residents of Makwane to use and maintain it.

Both the SIPP and BSFZ suffer from similar failure modes. The failure modes for both products are often due to the incorrect production and assembly of input materials. Therefore, the recommended actions to fix the effects of failures is for those who are responsible for production and assembly to make certain that the initial assembly of the SIPP and BSFZ is done according to the documented processes. In order to involve Makwane residents into the supply chain of the water treatment system, the training provided to residents must be accurate and disciplined. Those identified to train the residents must be well equipped with the necessary materials and knowledge in order to ensure that the risk problems identified for both the SIPP and BSFZ are eliminated from the production and assembly phase.

The risk complications of the borehole system are also man made. The design and construction of a borehole is conducted by highly skilled individuals who are signed to the Borehole Water Association of South Africa. Therefore, design and implementation of a borehole is often not the cause of risk problems for a borehole system. Risk complications develop during the normal operations of the system, especially when considering that the vandalising and theft of borehole systems is a common problem in rural areas. Though boreholes are reliable, they will not play a major part in including residents of Makwane Village in the processes of the water treatment system supply chain.

The ability to access input materials for the SIPP and BSFZ, where the vendors are as close as possible to the production site, is crucial in order to keep the water treatment system sustainable. Transportation costs must be minimized as they have a role in the final cost of both systems. Furthermore, it would be beneficial to limit the use of motor vehicles as most people coming from Makwane do not have regular access to motor vehicles. Borehole systems are implemented directly on site, therefore, the need to access vendors is reduced.

The accessibility of the borehole system by the end user becomes the crucial problem, especially if a borehole is implemented in a scattered rural community. The end users may be required to travel substantially to collect water, which does not change the current as-is processes. This is in contrast with the SIPP or the BSFZ where end users can use these systems inside their homes.

A well-developed water treatment supply chain for any rural community must have a positive social impact in the rural community in which it is implemented. Through the implementation of the SIPP or the BSFZ, residents can procure, manufacture, and distribute within the Makwane community at a profit. With time, experience, and the correct training, Makwane residents can manufacture these systems for other rural communities. The skills learnt by residents allow certain individuals to work in formal jobs and be rewarded for their skills. This is a central tenet of the water treatment supply chain, its ability to create economic opportunities for individuals cannot be underestimated. Therefore, the social impact of the supply chains of the SIPP and BSFZ is twofold. It improves the health of the community while, in tandem, creating economic avenues for the community to be active players in both the informal and formal economies. The social impact of borehole systems on the community limits itself to improving the health of the community. This remains a positive, as clean water eliminates waterborne diseases, which allows community members to play an active part in the economy.

The costs of initial implementation of the BSFZ, SIPP or borehole systems in the Makwane Village differ. A single implementation of the BSFZ costs approximately R40 000, the implementation of the SIPP system costs approximately R67 000, and the borehole system costs approximately R83 000 to implement. Added to this, it would probably be necessary to build more than one borehole in the area as the village is very scattered. This further increases the costs of implementing borehole systems, especially when maintenance and vandalism are taken into account.

Although a one-time deployment of any water treatment system is a meaningful objective, the true value of the supply chain lies in its ability to remain sustainable, by continually producing the treatment systems when needed. This allows residents to play a part in the supply chain processes, as a result creating a positive social impact in the community. In order to create sustainability, the supply chain must be able to pay for itself after an initial donor funded cash injection in the first year.

Sustainability can be achieved in one of two ways. The first option is to increase the mark-up on cost for either the SIPP or BSFZ as depicted in the cost models of figures 4.22 - 4.34. This solution is unsustainable because the affordability of the SIPP and BSFZ. Rural residents who typically have low incomes will not be able to afford these products when mark-up is at 110%. The second and more viable option is to expand the demand base. The Makwane production site can be set up to produce the SIPP and/or the BSFZ for the whole region, incorporating other rural areas. This can be done through the design of a lean production system that has lower costs, but produces at a high output.

## 4.6 Conclusion

After thorough research into centralized and decentralized water purification systems, three systems were identified and shortlisted as most suitable to be selected for deployed in Makwane Village. The water purification systems that were identified included the Biosand Filter with Zeolites (BSFZ), the Silver Impregnated Porous Pot (SIPP), and the borehole system. Only one of them can be selected.

Each of the shortlisted systems were analysed systematically to determine how they would be deployed in Makwane Village if selected. The analysis took the form of a supply chain study where activities such as procurement, manufacturing, packaging, transport, and delivery were analysed for each system. Following this, each of the three supply chains were analysed separately against four criteria that were deemed most important for the delivery of goods in rural African villages. The criteria were risk, social impact, cost, and product effectiveness. The outcome was a methodical analysis of the water purification products and their supply chains.

It was discovered that borehole systems are the most expensive to deploy, but provide good risk and effectiveness. In deploying a borehole system in Makwane, there will be little skills transfer into the community, because the development of a borehole system requires a certain skill set that cannot easily be transferred. Further to this, boreholes require an extensive maintenance procedure, which is not always possible in rural areas. The SIPP system is cheaper to deploy than the borehole system, and its deployment creates an opportunity for the Makwane community to play an active role in the supply chain, especially in the procurement and manufacturing phases. The SIPP system does have risk concerns and only produces only 20 litres of water per day. The BSFZ system has the cheapest supply chain, but has similar risk problems as the SIPP.

The next chapter concerns itself with the selection of the appropriate water purification system from the shortlist, given its supply chain. The selection process is methodical in order to ensure that the right product is chosen.

# Chapter 5

# Decision Making Models

## 5.1 Introduction

The successful selection of a water purification system in Makwane Village was dependent on a number of steps. The first step was the elicitation and analysis of user needs by understanding the demographics of Makwane village. The second step was to identify and analyse an exhaustive list of robust water purification systems that are capable of functioning in a rural African setting. The third step was to identify the criteria to be used to select the ideal purification system to be deployed. The fourth step was to design the decision making model that would be used to facilitate the selection of the ideal purification system for Makwane. The first three steps were addressed in chapters two, three and four. The fourth, and final step, is addressed in this chapter.

The original Analytic Hierarchy Processes (AHP) developed by Saaty (1977) is a decision making model that lended itself very well to the objectives of this project. The AHP process effectively prioritizes a set of alternative choices using a quantitative ratio scale based on a set of criteria that is determined by expert decision makers. Group members, or individuals, use their knowledge and experience in the subject matter to disseminate a particular selection problem into a hierarchy, and proceed to solving it using the AHP steps (Saaty, 1977).

Through investigation, the AHP methodology fell short in fundamental areas (Lootsma, 1997) (Saaty, 1977):

1. AHP uses the linear scale (1-9) to represent the preferences of the decision makers. It has been argued that this scale does not accurately represent the thinking process of the human mind when it comes to making preferences between alternative choices. Humans are said to think in an exponential manner as opposed to linear.
2. The problem of left-right asymmetry of the AHP model has been questioned by mathematicians. The preference made by a decision maker of alternative

$A_j$ over $A_k$ may not be the same in reverse. This means that reversing the logic of thinking ($A_k$ over$A_j$) does not always lead to the expected value. This has been labeled the Peron-Frobenus problem

3. The order in which individual preferences are aggregated in AHP sometimes produces different results.

More information on these concepts is provided by Lootsma (1997). The Additive and Multiplicative AHP are improved versions of the original AHP that addressed the problems stated, especially the grading of alternatives. The multiplicative AHP uses an exponential scale as opposed to a normal linear scale. The additive AHP is a logarithmic translation of the multiplicative AHP, this makes it easier to manipulate mathematically.

The AHP, whether in its additive or multiplicative extensions, is a deterministic model, and are, therefore, not capable of modelling the vagueness of preferences (Lootsma, 1997). Further to this the Vagueness, or imprecision, was due to the fact that sometimes, the outcome of an experiment cannot be properly observed. An example is the situation that comes into being after the experiment of casting a die with coloured faces under twilight conditions where colours cannot be properly distinguished. It becomes rather difficult to identify the colour of the die, and therefore, one cannot determine the outcome of the experiment (Lootsma, 1997). There may be numerous possible outcomes, each with a degree of truth. Similarly, the distance metric used for our social impact criteria may be viewed differently by different people. For example, a decision maker may be of the opinion that 200 meters is too far to travel to collect water, while someone else may think this distance is fair, while yet another decision maker believes the proposed distance is not far at all.

Fuzzy set theory, as presented by Zadeh (1965), alternatively referred to as fuzzy logic, is concerned with modelling the level of truth that a particular outcome belongs to a particular classification. This theory is suitable to model the vagueness of preferences that are part of human decision making, because it allows uncertainty in decision making by letting the decision maker input a range of quantitative preferences for a specific criteria. Fuzzy AHP allows a decision maker to make more than one quantified preference for a specific alternative

Classic AHP has problems with consistency. The linear scale that is used to make pairwise comparisons between alternatives does not represent general human thought processes. Human thought processes are better modelled by exponential grades as is done with multiplicative AHP. Additive AHP is the logarithmic equivalent of multiplicative AHP, this makes it easier to mathematically manipulate the criteria grades derived from multiplicative AHP. AHP uses the mean of individual grades provided by decision makers to come to a final grade for an alternative. This negates the preferences of individual decision makers. Fuzzy logic takes into account individual preferences through the use of the truth table that is then transformed into membership functions that represent individual preferences

Fuzzy Interference Systems (FIS) implement fuzzy logic using a MATLAB based neuro network model. It can be thought of as the rule evaluation of a fuzzy system Neuro-adaptive learning techniques such as FIS provide a method for the fuzzy modelling procedure to learn information about a data set. The ANFIS model uses and discretises linguistic variables as opposed mathematical variables to train the system to identify patterns (Jayawadena et al, 2014).

## 5.2 Materials and Methods

### 5.2.1 Methodology

In this chapter we sought to make a final decision with regards to which water purification system was to be deployed in Makwane Village. In order to do this, we applied the concepts of Additive and Multiplicative AHP to determine which purification system is most appropriate, using the criteria that were unveiled and analysed in chapter four.

Further to this, we extended the Additive and Multiplicative AHP model to a fuzzy neural network model that created a generic method of ranking all HWTSs that are outside of scope of this thesis. This model consistently ranked and classified all

HWTSs relative to each other using the stated criteria. A user that had analysed a particular HWTS using the criteria mentioned in chapter four can input the results of the analysis into the fuzzy neural network model that will provide, as an output, the classification and ranking of this particular HWTS relative to others.

The focus on this project was restricted to fuzzy numbers with triangular and trapezoidal membership functions. A fuzzy number ($\tilde{a}$) is characterized by three parameters: the lower value $a_l$, the modal value$a_m$, and the upper value $a_u$. Therefore, the fuzzy number ($\tilde{a}$) is represented as an ordered triplet of triangular, fuzzy numbers, stated in the form ($a_l$,$a_m$, $a_u$) (Lootsma, 1997).

The Additive AHP is similar to the SMART decision making model, where the pairwise comparisons of alternatives, are based on difference information. There is a logarithmic connection between the Additive AHP and Multiplicative AHP. The relative importance of criteria has scaled values assigned to it in the form of relative preference ($q_{jk}$) or difference of grades ($r_{jk}$) (table 5.1) (Lootsma, 1997). The scaled values presented in table 5.1 were obtained using the practices applied in the SMART methodology

The decision maker's preference for alternatives could be conveyed either in relative preference ($q_{jk}$) (used for multiplicative AHP) or its logarithmic alternative, the difference of grades ( $r_{jk}$) – used in additive AHP. Scale values are assigned to both equations, as depicted in table 5.1. In this chapter, the scaled values of the difference of grades ($r_{jk}$) were used to compare alternatives, and come to a final preference using Additive AHP. We then take advantage of the logarithmic connection between Additive AHP and Multiplicative AHP to come to a final decision using Multiplicative AHP results.

*Table 5.1: Relative preferences with scale values assigned to them. The Preferences are based in real magnitudes as ratios of subjective values and in logarithmic form as difference of grades*

| **Comparative Judgement of $A_i$ with respect to $A_k$** | **Relative preference for $A_i$ w.r.t $A_k$ in words** | **Relative preference $r_{jk}$ in real magnitudes** | **Difference of grades $q_{jk} = {}^2log r_{jk}$** |
|---|---|---|---|
| $A_j$ much more reliable | Strong preference for $A_j$ | 64 | 6 |
| $A_j$ more reliable | Strict preference for $A_j$ | 16 | 4 |
| $A_j$ somewhat more reliable | Weak preference for $A_j$ | 4 | 2 |
| $A_j$ as reliable as $A_k$ | Indifference | 1 | 0 |
| $A_k$ somewhat more reliable | Weak preference for $A_k$ | 1/4 | -2 |
| $A_k$ more reliable | Strict preference for $A_k$ | 1/16 | -4 |
| $A_k$ much more reliable | Strong preference for $A_k$ | 1/64 | -6 |

Decision makers compared the stated criteria against each other to determine which was more important. The decision maker used pairwise comparisons to determine the relative weighting that each stated criteria will have in the selection of the appropriate water purification system. This was done using the scaled values of the difference of grades (table 5.1). The arithmetic row mean of each criterion was then calculated. The arithmetic means were shifted by a constant to obtain grades between 4 and 10. The final criterion weights were obtained by using arithmetic means as exponents of $\sqrt{2}$, this was done because the grades of relative importance were made up of a geometric sequence with a progression factor of $\sqrt{2}$. The criterion weights were normalized to obtain a final relative weight for each criterion.

The next step was the decision processes, where the alternative water purification systems were evaluated under each criterion. The arithmetic row means of each alternative was calculated under each criterion and were then shifted by a constant to obtain smart grades (Additive AHP), randomly chosen between 0 and 10. The range 0-10 was used because humans are used to think in decimals and percentages. Multiplicative AHP grades were calculated using arithmetic means as exponents of $\sqrt{2}$. These multiplicative AHP grades were then normalized.

The aggregate scores for each alternative are calculated using the equation:

$$s_j = \sum_{i=1}^{m} c_i g_{ij}\,, \; j = 1, \dots, n \tag{5.1}$$

In equation 5.1, the aggregate grade of a particular alternative was computed using the grade that was given to that alternative under a certain criterion ($g_{ij}$), multiplied by the criteria weight ( $c_i$). This was then summed to obtain an aggregate grade for that particular alternative. The same process is repeated for every alternative. After this, the final arithmetic mean, SMART grade (Additive AHP score), and AHP score (Multiplicative AHP) was calculated to depict the preferred alternative. The ranking of criteria as well as alternatives from decision makers was done by calculating a mean of the individual inputs of each decision maker.

The degree of truth of a statement can be quantified within a particular range. For example, the importance (weight) that a certain criterion has in the overall selection process of a suitable HWTS can be modelled in the range (1, 2…., 10), where 1 depicts a low level of importance, and 10 is a very important criterion. The range is an outcome of the different points of view of a specific criterion, taken by a specific decision maker or decision makers (Lootsma, 1997). The AHP model did not take into account the changes in the range of preferences $(i.e.\ P_{min}\,, P_{max})$ that can be prescribed by a decision maker for a specific criterion or alternative. In essence, the AHP model did not take into account the fact that human beings can change their mind about criteria weights, or alternatives, given certain constraints. Fuzzy set theory did, on the other hand, take into account the changes in grading preferences

The fuzzy logic model centers on the creation of the membership function. The membership functions represent the change of preferences of decision makers. A membership function is attained when a preference grade is fuzzified. This is where, instead of entering a single grade, an ordered triplet of triangular fuzzy numbers stated in the form $(a_l, a_m, a_u)$ where there is a lower, modal, and upper number entered to represent a single grade. The fuzzy logic analysis then follows the same process as noted above, except that the difference of grades ( $\bar{r}_{jkd}$), relative preference ( $q_{jkd}$), criteria weights ($\tilde{c}_i$) and final scores ($\tilde{s}_i$) are represented by a lower modal and upper value as depicted in the equations below.

$$\bar{r}_{jkd} = (r_{jkdl}, r_{jkdm}, r_{jkdu}) \tag{5.2}$$

$$q_{jkd} = \left(q_{jkdl}, q_{jkdm}, q_{jkdu}\right) = (lnr_{jkdl}, lnr_{jkdm}, lnr_{jkdu}) \tag{5.3}$$

$$\tilde{g}_{ik} = (g_{ijm} - \frac{\sigma}{2},\ g_{ijm}, g_{ijm} + \frac{\sigma}{2}) \tag{5.4}$$

$$\tilde{c}_i = c_{im}(\ (\sqrt{2})^{-\sigma/2}, 1, (\sqrt{2})^{\sigma/2}) \tag{5.5}$$

$$\tilde{s}_i = \sum_i \tilde{c}_i \tilde{g}_{ij} = \sum_i c_{im} * (\ ((\sqrt{2})^{-\sigma/2}, 1, ) * \left(g_{ijm} - \frac{\sigma}{2},\ g_{ijm}, g_{ijm} + \frac{\sigma}{2}\right)) \tag{5.6}$$

$$\tilde{s}_{jm} = \sum_i c_{im} g_{ijm} \tag{5.7}$$

$$\tilde{s}_{jl} = \max(4, (\sqrt{2})^{-\sigma/2}\left(s_{jm} - \frac{\sigma}{2}\right)) \tag{5.8}$$

$$\tilde{s}_{ju} = \min(10, (\sqrt{2})^{\sigma/2}\left(s_{jm} + \frac{\sigma}{2}\right)) \tag{5.9}$$

Fuzzyfying a single grade can be done in three ways. The first is the mean and standard deviation method, the second is the range and mean approach, and third is the percentage of total method. The mean and standard deviation approach creates a mean and standard deviation from the list of grades calculated from inputs of various decision makers. The range and mean approach gathers the minimum and maximum grades provided by decision makers and then calculates a mean from the collection of those provided by decision makers. The percentage of total method calculates the percentage of the grade that falls within a predefined range, this break down the criteria range into subsets. The percentage of the grade approach was used to break down the criteria ranges into subsets for this study.

In the fuzzy model, each criteria presented in chapter four was broken down into a range. For example, the cost criteria was broken down into the cost range (R 0, R 100 000). This range incorporated all costs of water treatment systems, and was developed after a thorough analysis of the purchase costs of HWTS. Pursuant to this, the decision makers were asked to breakdown the cost range, into cost subsets, and assign a name and sub range to each subset. For example, the cost range was broken down into 4 subsets that corresponded to the decision makers' perception of the cost hierarchy. The first subset was the Inexpensive subset, which represented HWTS costs that range between R0 and R30 000. The Inexpensive Subset represented HWTS costs between R20 000 and R50 000. Similarly, the remaining subsets were assigned a cost range that was within the original (R 0, R 100 000) range.

It should be noted that the subsets were not mutually exclusive; for example, some numbers in the Inexpensive subset range were also included into the moderately expensive Subset range. This was due to the fact that, as explained above, not all people see costs the same, what some decision makers considered inexpensive, others viewed it as moderately expensive. This is why a fuzzy model was best suited to model the different degrees of truth expressed by decision makers. All costs that decision makers considered to be Inexpensive were added to the Inexpensive subset. Similarly, this was done for all other subsets of the cost criteria, even though there may have been some overlapping of costs in different subsets. The same process was followed for the remaining criteria. For example, the risk criteria (measured in RPN) was broken down into subsets using the input of our decision makers into the Unreliable, low risk, average Risk, high Risk subset ranges.

For each individual criterion, a truth table was developed. A truth table investigates the level of truth that a certain amount falls within a particular subset. Membership functions are subsequently developed for each subset range within a criterion. A membership function is the mathematical presentation of a truth table. Membership functions are the driving force of the fuzzy model because they are used to classify each HWTS under analysis. For example, if a particular HWTS costs R10 000 and has a low RPN, it will be assigned to the Inexpensive cost subset range and the Unreliable subset range. Membership functions are also represented graphically.

Subsequent to the development of the fuzzy model, the fuzzy sets of each criterion was used as inputs into the neural network model (Fuzzy Interference System). The neural network analyses the fuzzy sets of each criteria using alpha (α) cuts. An alpha cut of membership function is a set of discrete approximations of a continuous variable. For example, if a cost membership function is developed for costs between the domains $0 \leq x \leq 2000$, an apha cut of this membership function would be the selection of any number within this domain. The neural network model repeatedly takes different combinations of alpha cuts of the fuzzy sets of each to determine whether each HWTS under analysis falls in the “highly preferred”, “preferred”, “low preference” or “rejected” categories. These categories were selected by the decision makers to group the outcomes of the analysis of the HWTS.

An alpha cut simply mimics the analysis done in chapter 4 for each HWTS. For example, for a particular HWTS, its deployment cost may be R25 000, its risk 50 RPN, accessibility 1000 km, and production effectiveness 100 litres produced per day. This means that a single alpha cut is assigned to each criterion, creating a total of four alpha cuts per analysis. Using the criteria developed by decision makers for the determined outcome choices, this particular HWTS could be assigned to one of those four groups (i.e. highly preferred, preferred, low preference, rejected).This is when the neural network model plays an important part, as it automatically and repeatedly assigns alpha cuts (four at a time) per HWTS, and based on where these alpha cuts were assigned, it allocates the HWTS to an outcome choice

The neural network (FIS) model was developed on the MATLAB platform. The purpose of this model was for it to generate a rules based engine on which the appropriate HWTS would be selected. Further to this, the fuzzy neural network model would be able to help with the selection of any HWTS, provided that this HWTS has been analysed using the four mentioned criteria.

### 5.2.2 Data Collection

All criteria weights and scores were derived from expert decision makers. This is in accordance with the stated processes of all versions of AHP as the models require the expert input from decision makers. The same decision makers were selected to be the final decision makers with regard to which water purification system was to be deployed at Makwane Village. These individuals have extensive knowledge of household water purification systems, including design specification, as well as the current socio-economic environment at Makwane Village.

## 5.3 Results

### 5.3.1 Additive and Multiplicative AHP Models

*Table 5.2: Determining Criterion Weights*

| Criterion | Cost | Risk | Social impact | Effectiveness | Arithmetic Row Means | Grades After a Shift | Criterion Weights | Criterion Weights Normalized |
|---|---|---|---|---|---|---|---|---|
| **Cost** | 0 | 2 | 3 | 2 | 1.750 | 7.750 | 1.834008086 | 0.425 |
| **Risk** | -2 | 0 | 2 | 0 | 0.000 | 6.000 | 1 | 0.232 |
| **Social Impact** | -3 | -2 | 0 | 2 | -0.750 | 5.250 | 0.771105413 | 0.179 |
| **Effectiveness** | -2 | 0 | -2 | 0 | -1.000 | 5.000 | 0.707106781 | 0.164 |

*Table 5.3: Selection of the Appropriate Water Purification System using Additive and Multiplicative AHP*

| Criterion | Weight | Alternatives | SIPP | BSFZ | Borehole | Arithmetic Row Means | Additive AHP Scores | Multiplicative AHP Scores | Multiplicative AHP Scores Normalized |
|---|---|---|---|---|---|---|---|---|---|
| **Cost** | 0,425 | **SIPP** | 0 | -4 | 2 | -0,667 | 5,333 | 0,794 | 0,182 |
| | | **BSFZ** | 4 | 0 | 6 | 3,333 | 9,333 | 3,175 | 0,727 |
| | | **Borehole** | -2 | -6 | 0 | -2,667 | 3,333 | 0,397 | 0,091 |
| **Risk** | 0,232 | **SIPP** | 0 | 2 | -2 | 0,000 | 6,000 | 1,000 | 0,286 |
| | | **BSFZ** | -2 | 0 | -4 | -2,000 | 4,000 | 0,500 | 0,143 |
| | | **Borehole** | 2 | 4 | 0 | 2,000 | 8,000 | 2,000 | 0,571 |
| **Social Impact** | 0,179 | **SIPP** | 0 | -2 | 4 | 0,667 | 6,667 | 1,260 | 0,308 |
| | | **BSFZ** | 2 | 0 | 6 | 2,667 | 8,667 | 2,520 | 0,615 |
| | | **Borehole** | -4 | -6 | 0 | -3,333 | 2,667 | 0,315 | 0,077 |
| **Effectiveness** | 0,164 | **SIPP** | 0 | -4 | -6 | -3,333 | 2,667 | 0,315 | 0,077 |
| | | **BSFZ** | 4 | 0 | -2 | 0,667 | 6,667 | 1,260 | 0,308 |
| | | **Borehole** | 6 | 2 | 0 | 2,667 | 8,667 | 2,520 | 0,615 |
| **Aggregate** | 1,000 | **SIPP** | 0 | -2,251 | 0,118 | -0,711 | 5,289 | 0,782 | 0,241 |
| | | **BSFZ** | 2,251 | 0 | 2,369 | 1,540 | 7,540 | 1,705 | 0,527 |
| | | **Borehole** | -0,118 | -2,369 | 0 | -0,829 | 5,171 | 0,750 | 0,232 |

There were five decision makers in total, they consisted of two end users from Makwane, one with knowledge of manufacturing of the SIPP and BSFZ, one from a logistics background and one who was involved with the design of the SIPP and BSFZ. Table 5.2 depicts the results given when the decision makers compared the stated criteria against each other to determine which should have the highest weighting. The decision makers used pairwise comparisons to determine the relative weights that each criteria will have in the selection of the appropriate water purification system. The first part of the table contains a 4x4 matrix, where the stated criteria are compared against each other. This comparison was done using the scaled values of the difference of grades presented in table 5.1. For example, when the cost criterion in the row was compared to the social impact criterion in the column, the value three was given by the decision makers when these two criteria are compared. This meant that the cost criterion is three times as important as social impact criteria according to the decision makers.

After the comparison of criteria against each other, the average (arithmetic mean) of each criterion was calculated. Subsequently, each criteria average was shifted by a constant of 6 in order to get in the range of (0, 10) as this made the numbers more manageable from an arithmetic point of view. After this, the $\sqrt{2}$ power of each arithmetic mean was calculated to achieve the weight of each criteria, the weights were then normalised to achieve the final weight of each criteria. According to the decision makers, cost was the most important criteria with a weight of 0,425, followed by reliability with a weight of 0.232. Social impact has a weighting of 0.179, and effectiveness had the lowest rating of 0.164.

Once the weights of each criterion had been calculated, the next step in the process was to determine which water purification system will be chosen. Table 5.3 depicts the results of the selection process using Additive and Multiplicative AHP models. Decision makers compared the three alternative water purification systems to determine which alternative was preferred given a particular criterion. For example, under the cost criterion, the SIPP was preferred to the borehole, and was given a value of two. After the three alternatives were compared against each other under each criterion, the arithmetic mean was calculated per alternative under each criterion. Subsequently, each arithmetic mean is shifted by a constant of six again to achieve the final results of the Additive AHP.

The Additive and Multiplicative AHP have a logarithmic relationship. Therefore, to calculate the results of the Multiplicative AHP the $\sqrt{2}$ power of each arithmetic mean was calculated. The results of the Multiplicative AHP were then normalised to achieve the final results of the Multiplicative AHP. After the calculation of the Multiplicative and Additive AHP under each criterion was concluded, the aggregate scaled values, arithmetic mean, Additive, and Multiplicative AHP were calculated. The aggregate Additive AHP scores were 5,289 (SIPP), 7,540 (BSFZ), and 5,171 (boreholes). The aggregate normalised Multiplicative AHP scores were 0,241 (SIPP), 0,527 (BSFZ), and 0,232 (borehole). According to both the Additive and Multiplicative AHP, the BSFZ is the preferred water purification system chosen by the decision makers to be deployed at Makwane Village.

### 5.3.2 Using Fuzzy Logic and Neural Network Analysis to help with Decision Making

The fuzzy analysis began with segmenting the cost criteria into an applicable range. After analysis of various HWTSs it was discovered that most HWTS deployment systems fit within the (R 0, R100 000) cost range for deployment in a scattered rural system such as Makwane village. The cost range was then divided into increments of R5 000 from R0 to R100 000. Subsequent to this, the decision makers were asked to breakdown the cost range into cost subsets, and assign a name and sub range to each subset. In this case, the cost range was broken down into 4 subsets that corresponded to the decision makers' perception of the cost hierarchy. For example, the HWTS deployment systems that was in the R0 or R10 000 cost ranges were regarded as inexpensive, and were therefore, assigned to the inexpensive column by decision makers. Table 5.4 depicts the truth table of water treatment system deployment cost criteria. The truth table helped to structure the outputs derived from the perception of decision makers. This is where decision makers assigned core, support and complimentary variables to certain costs within particular subsets. The following points further explain the role of the core support and complimentary:

- Y: this is a support function that belongs to the set ( $0 < u(x) < 1$). The truth variable ($u(x)$) is a numerical depiction of the level of truth, where 0 indicates not true and 1 indicates an absolute truth. “Y” is used when decision makers are somewhat sure that a particular cost falls within a certain subset. For example, a decision maker will add the “Y” variable if they feel that a HWTS of the cost of R10 000 might fall within the “inexpensive” cost subset.
- Y*: This is known as the core variable where the level of truth $u(x) = 1$, therefore, indicating the value is ideal representation to the particular subset.
- N: indicates a complementary variable where ($u(x) = 0$).

The purpose of the truth table was to align each linguistic subset to a subset of cost ranges. One can see from table 5.4 that, according to decision makers, the range (R0, R10 000) fits in the “inexpensive” subset. What this meant was that decision makers felt that any HWTS deployment system that costs between R0 and R10 000 can be regarded as totally inexpensive.

Table 5.5 is a mathematical representation of table 5.4, where the criteria subsets were aligned to the cost ranges using mathematical formula. For example, in the “inexpensive” subset when deployment costs, represented by $x$, are below R10 000, this was regarded as a true representation of this subset (Y* and $\mu(x) = 1$), when $x$ is above R10 000, but below R20 000, this is regarded as a possible true representation of the subset, though it is not an exact truth (Y and ($0 < u(x) < 1$). This reasoning is an outcome of the fact that some decision makers believe that this cost range may fit in this subset (i.e inexpensive), while others may feel that it doesn’t. When$x \geq R\ 20000$ , all decision makers are in agreement that this does not fit in the “inexpensive” subset (N and $\mu(x) = 0$). Similar reasoning can be used to read the remainder of table 5.5. Figure 5.1 is a graphical representation of tables 5.5 and 5.4, where the truth value,$u(x)$, is on the vertical axis, and the cost range, $x$, is plotted on the horizontal axis. Each criterion subset is highlighted in a different colour.

Table 5.6 depicts the truth table for the risk of the HWTS as regarded by the decision makers. Risk is measured in RPN, and the RPN range is (0, 300). The risk criterion was divided into 5 subsets that represent the different levels of the operational risk as regarded by the decision makers. The decision makers then assigned the RPN values to these subsets. Table 5.7 depicts the membership functions of the rik criterion, similar to the cost criterion, it is the mathematical representation of the truth table. Figure 5.2 depicts the graphical representation of figures 5.6 and 5.7, where the truth value,$u(x)$, is on the vertical axis, and the RPN range, $x$, is plotted on the horizontal axis. Each criterion subset is highlighted in a different colour.

*Table 5.4: The Truth Table of the Water Treatment Systems Deployment Costs*

| Cost (R) | Inexpensive | Moderately Expensive | Expensive | Very Expensive |
|---|---|---|---|---|
| **0** | Y* | N | N | N |
| **10000** | Y* | N | N | N |
| **20000** | Y | Y | N | N |
| **30000** | N | Y | N | N |
| **40000** | N | Y* | Y | N |
| **50000** | N | N | Y | N |
| **60000** | N | N | Y* | N |
| **70000** | N | N | Y | Y |
| **80000** | N | N | N | Y* |
| **90000** | N | N | N | Y* |
| **100000** | N | N | N | Y* |

*Table 5.5: The Membership Function of the Water Treatments Systems Deployment Costs*

| Inexpensive | | Moderately Expensive | | Expensive | | Very Expensive | |
|---|---|---|---|---|---|---|---|
| $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ | $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ | $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ | $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ |
| $x \leq 10000$ | $1$ | $x \leq 20000$ | $0$ | $x \leq 40000$ | $0$ | $x \leq 70000$ | $0$ |
| $10000 < x \leq 30000$ | $1.5 - \frac{x}{20000}$ | $20000 < x \leq 40000$ | $\frac{x}{20000} - 1$ | $40000 < x \leq 60000$ | $\frac{x}{20000} - 2$ | $70000 < x \leq 80000$ | $\frac{x}{10000} - 7$ |
| $x > 30000$ | $0$ | $40000 < x \leq 50000$ | $5 - \frac{x}{10000}$ | $60000 < x \leq 80000$ | $4 - \frac{x}{20000}$ | $x > 80000$ | $1$ |
| | | $x > 50000$ | $0$ | $x > 80000$ | $0$ | | |

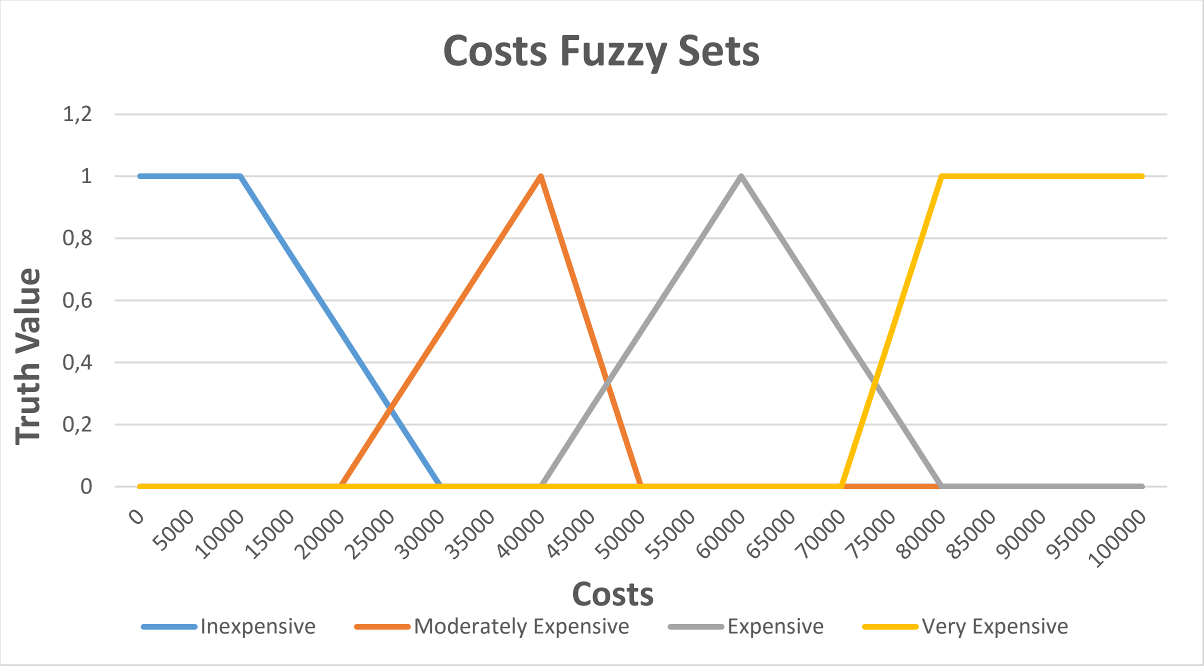


*Figure 5.1: Cost Fuzzy Sets*

Table 5.8 depicts the Accessibility truth table. The accessibility criterion measured how far, in meters, community households were from water sources. The overall accessibility of water sources ranges from 0 to 3000 meters. Decision makers segmented the accessibility criterion into four segments. As with the other criterions, decision makers were seldom equivocal about how distances should be allocated to various segments. For instance, some decision makers were of the opinion that distances $(x)$ between 50 meters and 100 meters should be assigned to the very very close segment, while some believed that it should be assigned to the very close segment. In order to depict this divergence of opinion, the variable Y was used to show uncertainty in decision making.

The accessibility segments are represented mathematically in table 5.9. For every distance value $((x))$, if the truth value $(u(x))$ is either 0 or 1 this represents certainty in the group decision making, if the truth value $(u(x))$ is represented by some sort of equation for certain ranges of distance $x$, this represents an uncertainty in group decision making where opinion varies between decision makers. Figure 5.3 depicts the graphical representation of tables 5.8 and 5.9. The uncertainty in group decision making is depicted graphically by the slanted lines in each segment. The slanted lines are the graphical representations of the equations where $u(x)$ is neither 0 nor 1. This is true for all other criteria.

The Production truth table is depicted in table 5.10 with its corresponding membership function in table 5.11. The production of typical HWTSs was determined to be in the range (0, 240) litres per day, the graphical representation of the production of HWTS was depicted in figure 5.4.

*Table 5.6: The Water Treatment Systems Risk Truth Table*

| Risk (RPN) | High Risk | Average Risk | Moderate Risk | Low Risk | Very Risky |
|---|---|---|---|---|---|
| **0** | Y* | N | N | N | N |
| **10** | Y* | N | N | N | N |
| **20** | Y* | N | N | N | N |
| **30** | Y* | N | N | N | N |
| **40** | Y* | N | N | N | N |
| **50** | Y* | N | N | N | N |
| **60** | Y* | N | N | N | N |
| **70** | Y* | N | N | N | N |
| **80** | Y* | N | N | N | N |
| **90** | Y | N | N | N | N |
| **100** | Y | Y | N | N | N |
| **110** | N | Y* | N | N | N |
| **120** | N | Y | Y | N | N |
| **130** | N | N | Y | N | N |
| **140** | N | N | Y* | N | N |
| **150** | N | N | Y | Y | N |
| **160** | N | N | N | Y | N |
| **170** | N | N | N | Y* | N |
| **180** | N | N | N | Y* | N |
| **190** | N | N | N | Y* | N |
| **200** | N | N | N | Y* | N |
| **210** | N | Y* | Y | Y* | Y |
| **220** | N | N | Y | N | Y* |
| **230** | N | N | Y* | N | Y* |

*Table 5.7: The Membership Function of the Water Treatment Systems Risk Criterion*

| **Low Risk** | | **Average Risk** | | **Moderate Risk** | | **High Risk** | | **Very Risky** | |
|---|---|---|---|---|---|---|---|---|---|
| $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ | $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ | $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ | $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ | $\boldsymbol{x}$ | $\boldsymbol{u(x)}$ |
| $x \leq 80$ | $1$ | $x \leq 100$ | $0$ | $x \leq 120$ | $0$ | $x \leq 150$ | $0$ | $x \leq 210$ | $0$ |
| $80 < x \leq 110$ | $\frac{110-x}{30}$ | $100 < x \leq 110$ | $\frac{x-100}{10}$ | $120 < x \leq 140$ | $\frac{x-120}{20}$ | $150 < x \leq 170$ | $\frac{x-150}{20}$ | $210 < x \leq 220$ | $\frac{x-210}{10}$ |
| $x > 110$ | $0$ | $110 < x \leq 130$ | $\frac{130-x}{20}$ | $140 < x \leq 160$ | $\frac{160-x}{20}$ | $170 < x \leq 210$ | $1$ | $220 < x$ | $1$ |
| | | $x > 130$ | $0$ | $x > 160$ | $0$ | $210 < x \leq 220$ | $\frac{220-x}{20}$ | | |
| | | | | | | $220 < x$ | $0$ | | |

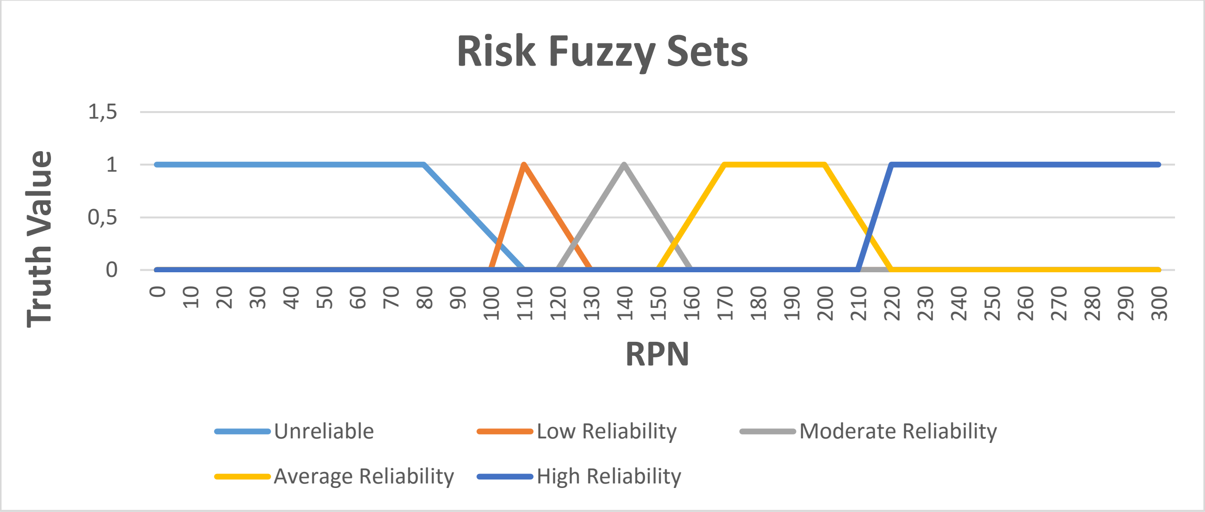


*Figure 5.2: Risk Fuzzy Sets*

*Table 5.8: The Accessibility of Water Treatment Systems Truth Table*

| **Distance** | **Very Close** | **Close** | **Moderately Far** | **Far** |
|---|---|---|---|---|
| **0** | Y* | N | N | N |
| **100** | Y* | Y | N | N |
| **200** | N | Y | N | N |
| **400** | N | Y* | N | N |
| **600** | N | Y* | Y | N |
| **800** | N | N | Y | N |
| **1000** | N | N | Y* | N |
| **1200** | N | N | Y* | N |
| **1400** | N | N | N | Y* |
| **1600** | N | N | N | Y* |

Table 5.9: The Accessibility Membership Function

| **Very Close** | | **Close** | | **Moderately Far** | | **Far** | |
|---|---|---|---|---|---|---|---|
| $x$ | $u(x)$ | $x$ | $u(x)$ | $x$ | $u(x)$ | $x$ | $u(x)$ |
| $x \leq 100$ | 1 | $x \leq 100$ | 0 | $x \leq 600$ | 0 | $x \leq 1300$ | 0 |
| $100 < x \leq 200$ | $\frac{200 - x}{100}$ | $100 < x \leq 400$ | $\frac{x - 100}{300}$ | $600 < x \leq 900$ | $\frac{x - 600}{300}$ | $1300 < x \leq 1400$ | $\frac{x - 1300}{100}$ |
| $x > 200$ | 0 | $400 < x \leq 500$ | 1 | $900 < x \leq 1200$ | 1 | $x > 1400$ | 1 |
| | | $500 < x \leq 700$ | $\frac{700 - x}{200}$ | $1200 < x \leq 1400$ | $\frac{1400 - x}{200}$ | | |
| | | $x > 700$ | 0 | $x > 1400$ | 0 | | |

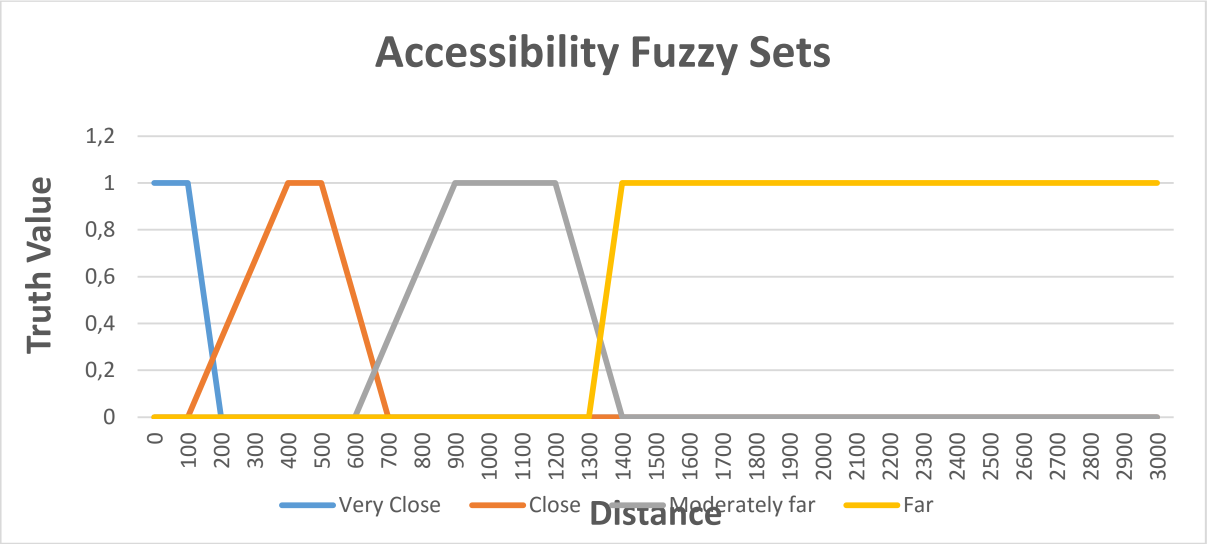


Figure 5.3: Accessibility Fuzzy Sets

*Table 5.10: The Production Truth Table*

| **Production (Day/L)** | **Low** | **Acceptable** | **High** | **Very High** |
|---|---|---|---|---|
| **0** | Y* | N | N | N |
| **10** | Y* | N | N | N |
| **20** | Y | Y | N | N |
| **30** | N | Y | N | N |
| **40** | N | Y* | N | N |
| **50** | N | Y* | N | N |
| **60** | N | Y* | N | N |
| **70** | N | Y* | N | N |
| **80** | N | Y | Y | N |
| **90** | N | N | Y* | N |
| **100** | N | N | Y* | N |
| **110** | N | N | Y* | N |
| **120** | N | N | Y* | N |
| **130** | N | N | Y* | N |
| **140** | N | N | Y* | N |
| **150** | N | N | Y | Y |
| **160** | N | N | N | Y* |
| **170** | N | N | N | Y* |
| **180** | N | N | N | Y* |

*Table 5.11: Production Membership Functions*

| **Low** | | **Acceptable** | | **High** | | **Very high** | |
|---|---|---|---|---|---|---|---|
| $x$ | $u(x)$ | $x$ | $u(x)$ | $x$ | $u(x)$ | $x$ | $u(x)$ |
| $x \leq 10$ | 1 | $x \leq 20$ | 0 | $x \leq 80$ | 0 | $x \leq 150$ | 0 |
| $10 < x \leq 30$ | $\frac{30-x}{20}$ | $20 < x \leq 40$ | $\frac{x-20}{20}$ | $80 < x \leq 90$ | $\frac{x-80}{10}$ | $150 < x \leq 160$ | $\frac{x-150}{10}$ |
| $x > 30$ | 0 | $40 < x \leq 70$ | 1 | $90 < x \leq 140$ | 1 | $x > 160$ | 1 |
| | | $70 < x \leq 90$ | $\frac{90-x}{20}$ | $140 < x \leq 160$ | $\frac{160-x}{20}$ | | |
| | | $x > 90$ | 0 | $x > 160$ | 0 | | |

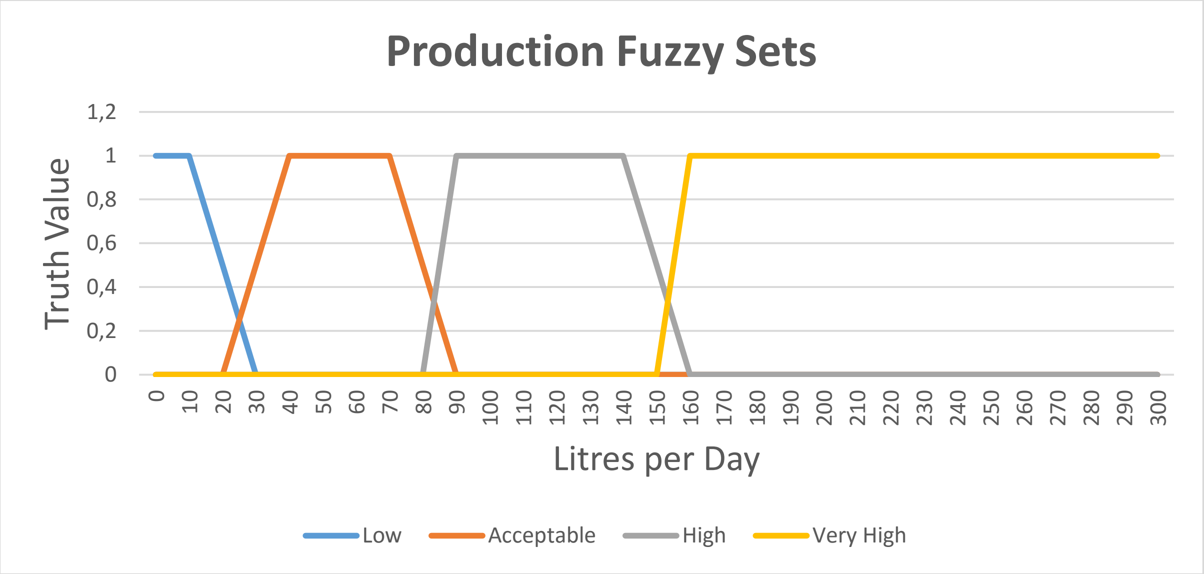


*Figure 5.4: Production Fuzzy Sets*

The fuzzy sets (membership functions) of all criteria were used as inputs into the neural network model. Figure 5.5 depicts a high level graphical representation of the Neural Network model as it is depicted on the MATLAB platform; in the form of a fuzzy inference system editor. The neural network model then develops a rules based engine (white box), based on the random application of alpha cuts, while remaining within the constraints provided by the membership functions of the various criteria. The outcome of the neural network model is the rules engine is depicted in appendix E.

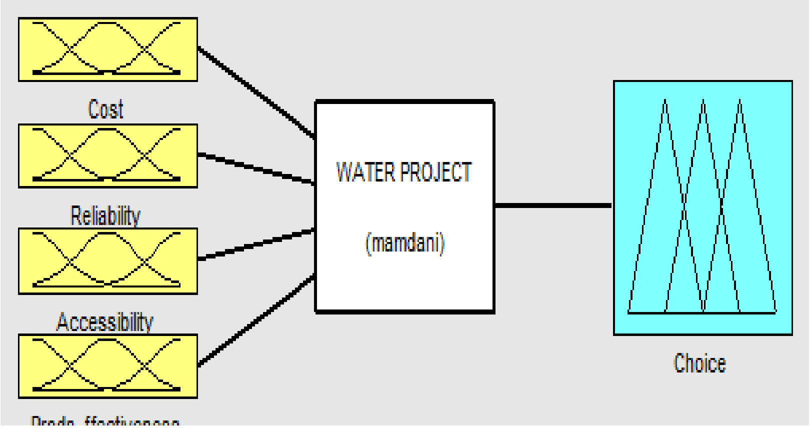


*Figure 5.5: Fuzzy Inference System Editor*

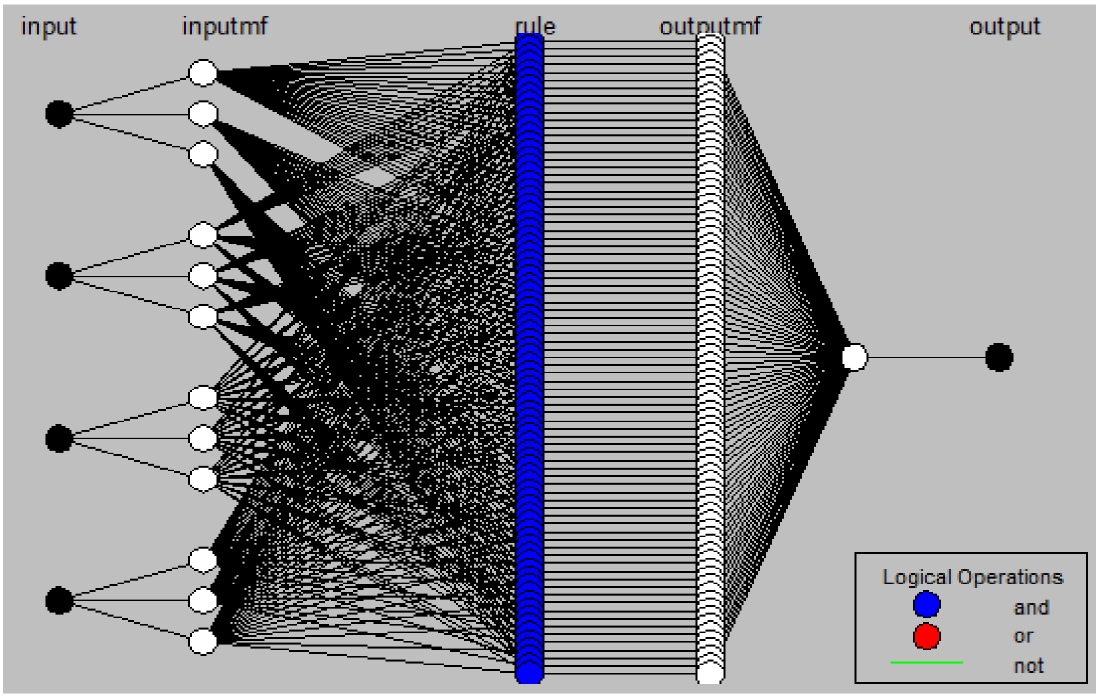


*Figure 5.6: ANFIS Architecture with Input and Output Membership Functions*

Figure 5.6 provides a more detailed visual depiction of figure 5.5. The figure starts with the depiction of the four input criteria. Various combinations of these input criteria were aggregated (using alpha cuts) to determine the output choices and the circumstances under which output choices are made. These circumstances under which choices are made constitute the rules engine. The rules engine uses fuzzy analysis to mimic the analysis conducted for the HWTSs in chapter four to determine in which choice categories a particular HWTS falls.

The choice (or preference) categories for the treatment systems under consideration were determined by decision makers. After each water treatment system was analysed it was assigned to a choice category to indicate the level of preference for the HWTS under analysis. Decision makers settled on four choice categories, they were: highly preferred, preferred, low preference, and reject. The neural model assigned each water treatment system under analysis to one of these four choice categories once it had been analysed. In order to facilitate the modeling on MATLAB, each choice group was assigned sequential ordered points. The Reject choice group was assigned points 0-25, the low preference choice was assigned points 25-50, the preferred choice group was assigned points 50-75, and the highly preferred choice group was assigned point 75-100. The choice groups, and its assigned points, are depicted in table 5.12.

*Table 5.12: Choice Groups*

| Preferred Choice | Assigned Points |
|---|---|
| Highly Preferred (HP) | 75 – 100 |
| Preferred (P) | 50 – 75 |
| Low Preference (LP) | 25 - 50 |
| Reject (R) | 0 - 25 |

The rules engine categorises the HWTSs that come under analysis. Any HWTS that has had its deployment cost, reliability, accessibility, and production effectiveness analysed can use this rules engine to determine the choice category in which this HWTS is allocated. The rules engine uses the subsets (represented by the membership functions) of each criteria to determine which category a particular HWTS should be allocated. Appendix E depicts the rules engine produced by the neural network model. For example, for a certain HWTS under analysis, if cost is in the Inexpensive category and Risk is in the Low Reliability category and Distance (i.e. acceptability) is in the Far category and flow rate is on the Acceptable category then the choice group output 1mf30. This means that this particular HWTS system has been assigned 30 total points, which means that it is allocated to the Low Preference (LP) choice

*Table 5.13: Summary of Feasibility Results*

| | **Deployment Costs (Rands)** | | **Risk (RPN)** | | **Accessibility (Meters)** | | **Production Effectiveness (litres/day)** | |
|---|---|---|---|---|---|---|---|---|
| | **Value (Rands)** | **Fuzzy Value** | **Value (RPN)** | **Fuzzy Value** | **Value (Meters)** | **Fuzzy Value** | **Value (Litres/Day)** | **Fuzzy Value** |
| **SIPP** | R 66 995,95 | Expensive | 166 | High Risk | 373 | Close | 20 | Acceptable |
| **BSFZ** | R 39 999,07 | Moderately Expensive | 96 | Low Risk | 373 | Close | 150 | Very High |
| **Borehole** | R 83 440,00 | Very Expensive | 130 | Moderate Risk | 150 | Close | unlimited | Very High |

The same procedure described above was conducted to determine which of the water treatment systems under consideration (SIPP, BSFZ, and borehole) was the better choice. Table 5.13 depicts the results of the feasibility analysis of each water treatment system conducted in chapter four combined with the fuzzy analysis. For each water treatment system, the table 5.13 displays the value of each criterion attained during the feasibility analysis, along with its corresponding fuzzy value. This was attained using the membership functions that represented the subsets of each criterion. Using rules engine derived from the neural network model, the HWTSs were ranked according to its preferred choice.

Figure 5.7-5.9 depicts the logic rule viewer for the SIPP, BSFZ and borehole systems from the neural network model from MATLAB. Considering a cost value of R66, 995. 95 with Risk of 166, accessibility of 373 and production effectiveness of 20, the fuzzy logic rule viewer assigned 2.33 points which means the SIPP falls in the reject category. With a cost value of R39, 999.07, Risk of 96, Accessibility 373, and Production Effectiveness of 150 the BSFZ is assigned 25 points meaning that is falls in the Low Preference choice category. The borehole system was assigned 2.33 points (Reject)

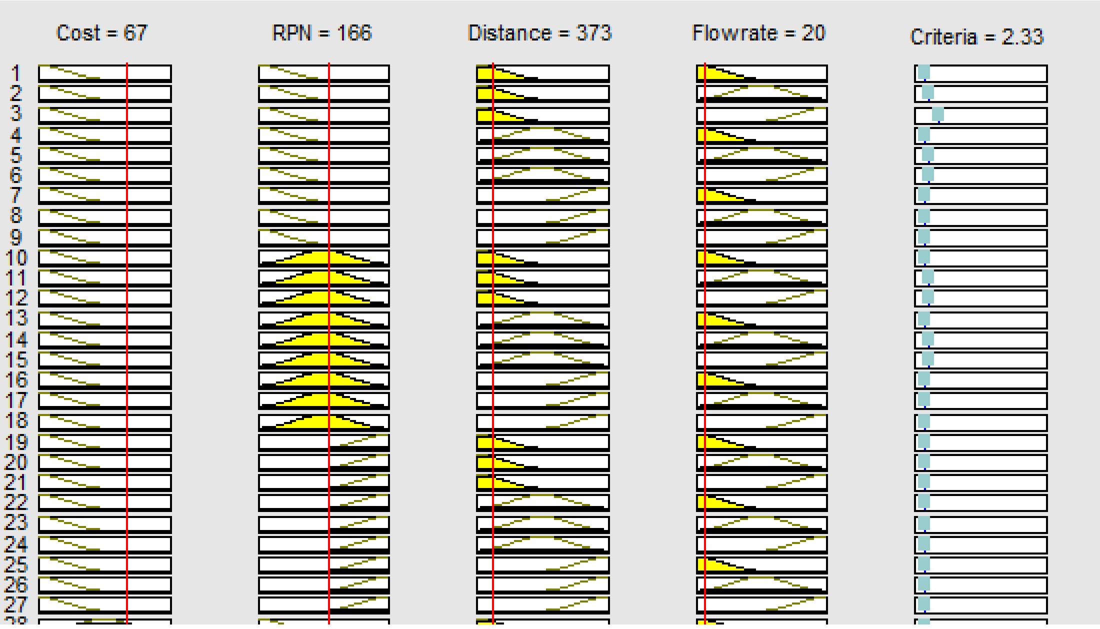


Figure 5.7: Logic Rule viewer for SIPP

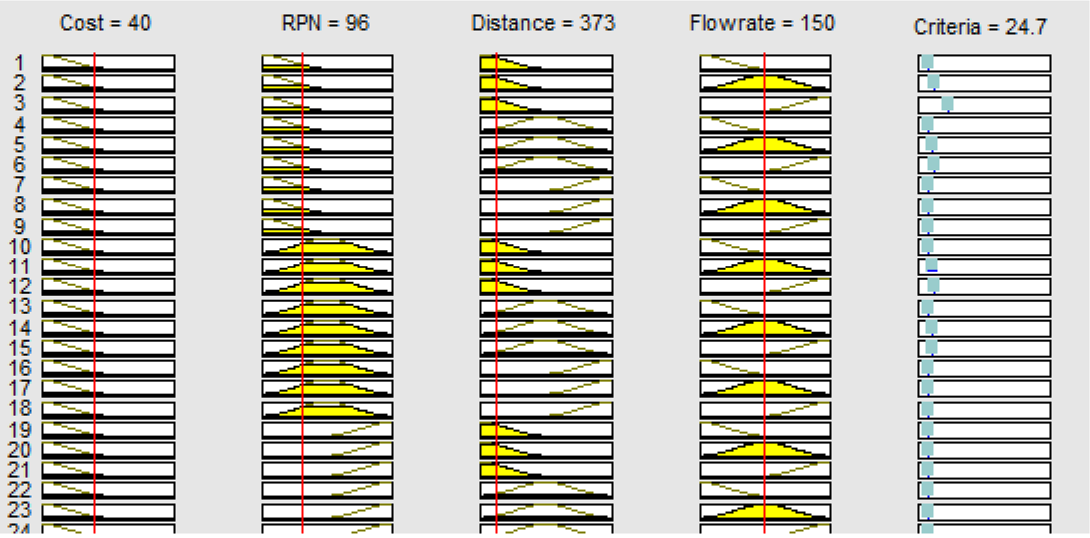


Figure 5.8: Logic Rule viewer for BSFZ

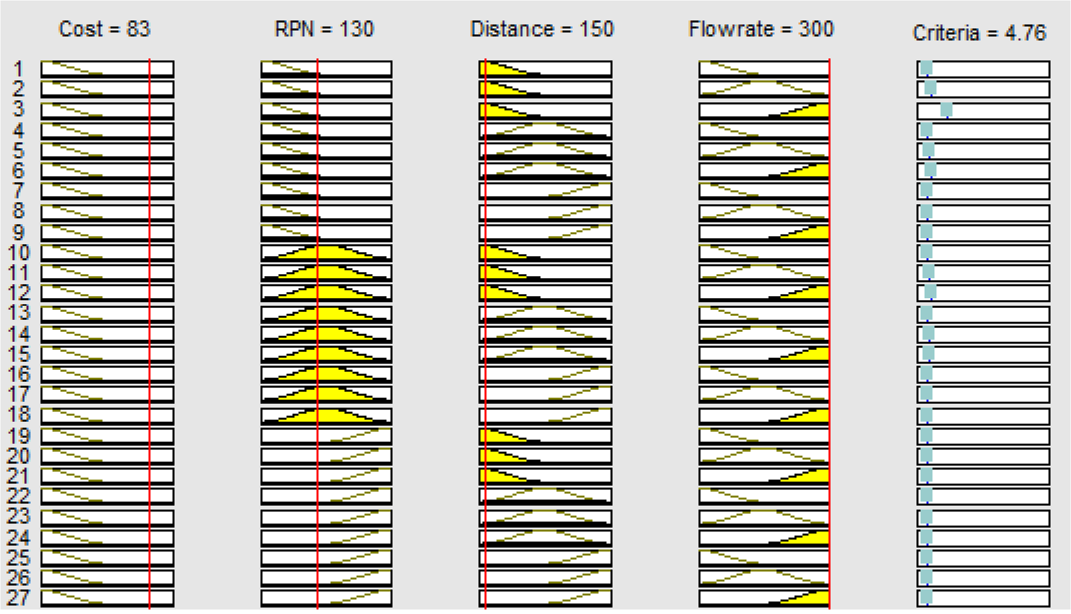


*Figure 5.9: Logic Rule viewer for Borehole*

This interaction is depicted on surface plots. In an input surface plot, the selected criteria were plotted on the x and y axes with the preferred choice on the z axis. The input surface plot does not show the interaction of the various criteria, but merely depicts where criterion are plotted on a plane. For example, figure 5.9 depicts the plotting of reliability, cost, and preferred choice, while figure 5.10 depicts the plotting of accessibility and cost choice.

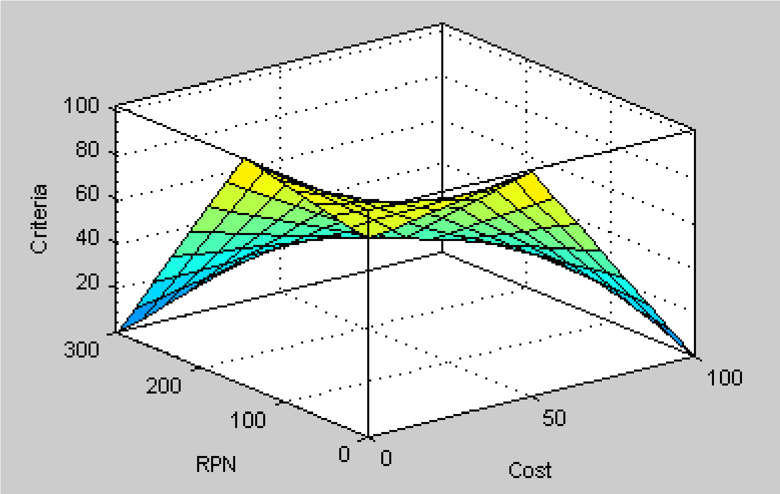


*Figure 5.11: 3D Output Surface Plot showing RPN (accessibility), Cost and choice (criteria)*

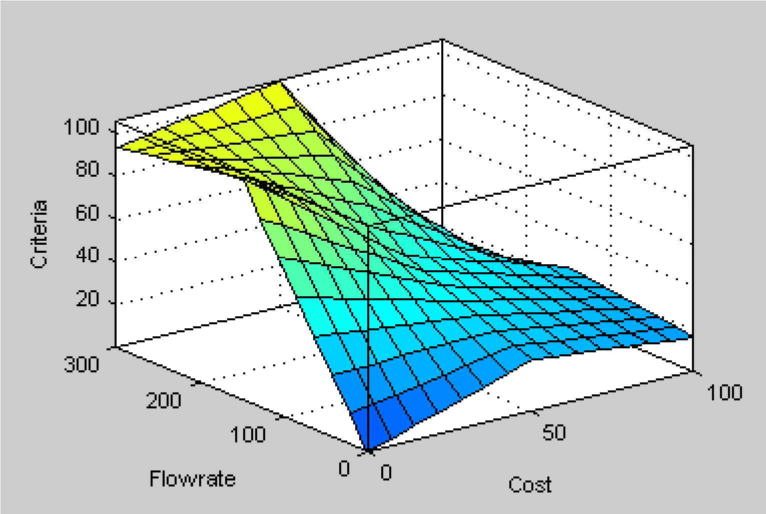


*Figure 5.12: 3D Output surface Plot showing cost, distance (accessibility) and choice (criteria)*

The output surface plots are 3D representations of the sensitivity rule viewer. Ideally the output surface for this analysis should be presented in 5D, with the four criteria and the preferred choice (criteria) each represented by a dimension plane. This is not possible in reality, therefore, the interaction of the criteria are depicted piecewise on 3D. The output surface plots show the interaction of selected criteria metrics and the effect they have on the preferred choice. For example, figure 5.11 depicts the interaction between RPN (Risk) and costs based on the membership functions of water treatment systems in the neural network model. One notices that water treatment systems will have a high choice value (criteria) when costs and risks interact at low levels. Similarly, figure 5.12 shows that a high preferred choice (criteria) is attained when the flow rate is high and costs are at moderate levels.  Figures 5.13 shows the interaction between flowrate and RPN, High choice values (criteria) is attained when flow rates are high and RPN is at moderate levels.

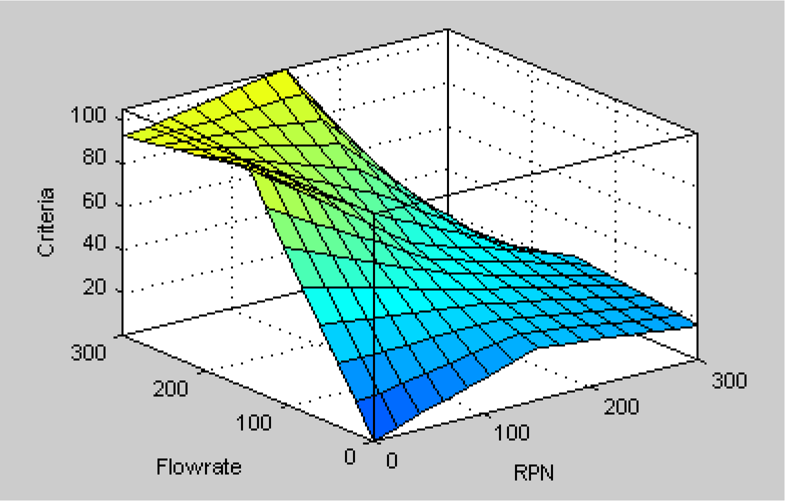


*Figure 5.13: 3D output surface Plot showing the interaction between RPN (risk), flow rate and its effect on Preferred Choice(Criteria)*

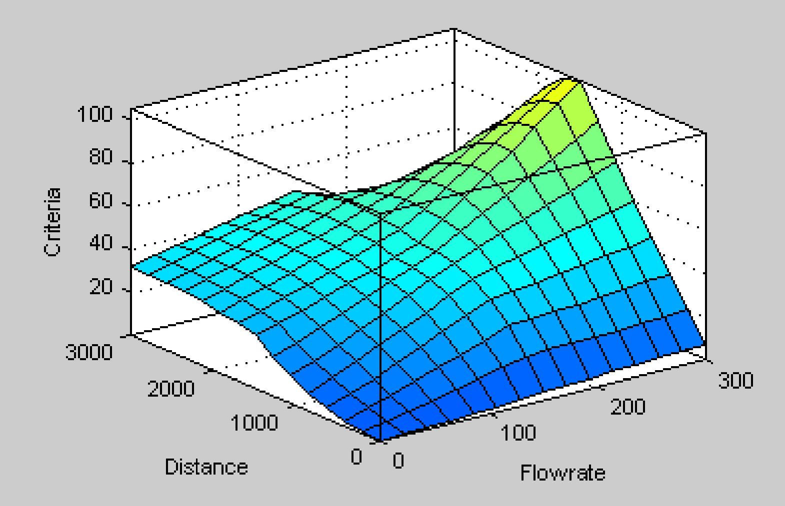


*Figure 5.14: 3D output Surface Plot showing the interaction between distance (accessibility), Flowrate and its effect on preferred choice*

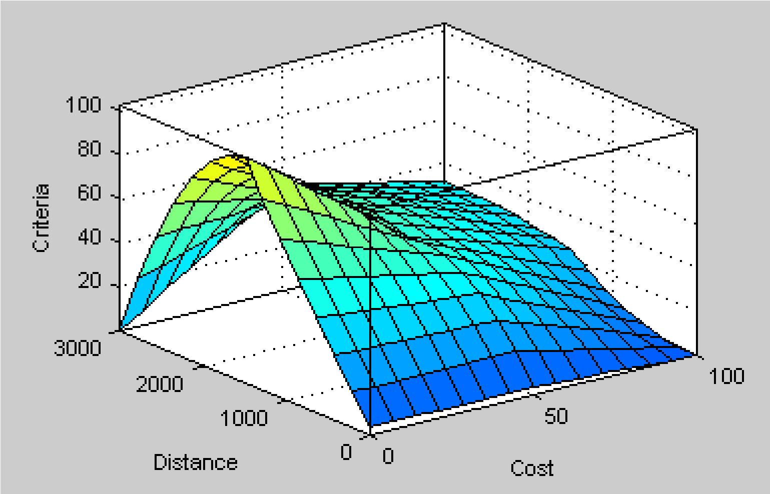


*Figure 5.15: 3D output Surface Plot showing the interaction between Distance, Cost and choice (criteria)*

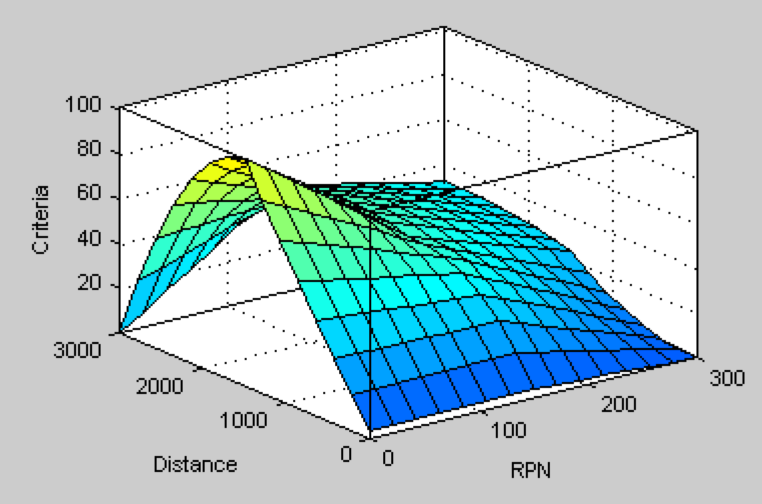


*Figure 5.16: 3D output Surface Plot showing the interaction between Distance, RPN and Choice (criteria)*

## 5.3 Discussion

The AHP models provided a systematic method of selecting the appropriate water purification system to be deployed in Makwane Village. The cost criterion was given the most weight by the decision makers. This is understandable because in poorer rural populations the cost of materials is often the defining factor. Rural populations are constrained by the high price of materials, therefore, if we were to deploy a water purification system in rural areas such as Makwane Village, and further require that the community played an active part in the operations of the supply chain that deploys water purification systems to rural areas, costs must remain manageable.

The supply chain processes of the BSFZ were the cheapest of the three alternatives. From the procurement of input materials, through to the production and delivery the of BSFZ systems to Makwane, the costs remained manageable when compared to the other systems.

The effectiveness of the water purification systems was regarded as the second most important criteria according to decision makers. Effectiveness was defined as the ability of the water purification system to perform according to specifications, in terms of daily water production and microbial removal. According to the results presented in table 4.15, the SIPP has a negligible advantage over the BSFZ when it came to microbial removal. However, the BSFZ was capable of producing over 150L of water per day, as required by the SANS. Borehole water had an advantage over both the SIPP and BSFZ when it came to effectiveness.  This was recognized by the decision makers as they collectively rated the borehole highest in terms of effectiveness, the BSFZ as the lowest. Even though the effectiveness criterion had a high weight, the BSFZ was chosen as the preferred HWTS to be deployed in Makwane. This was possibly due to the fact that even though the BSFZ was the least effective of the proposed water purification systems, it met the minimum requirements according to the SANS

The borehole was regarded as the most reliable system, followed by the BSFZ and the SIPP. The SIPP and BSFZ suffer from the same reliability problems, the only difference being that the potential reliability problems suffered by the BSFZ can be more easily overcome compared to those of the SIPP. Therefore, the BSFZ received the higher rating than the SIPP. The reliability problems suffered by the borehole system are usually attributed to theft and vandalism of critical parts, furthermore, the replacement of these parts takes long and the parts themselves are quite expensive.

The BSFZ and SIPP faced similar problem when it comes to accessibility. This is because household members will still have to travel an average of 373 meters to collect water to refill either system. It was assumed that the borehole would be built closer to the households in order to help minimize accessibility problems.

The AHP model, although quite adept at facilitating group decision making, did not provide an effective manner of modelling group indecision. The AHP model could not account for indecision by group members. Group members had to give one rating for each criterion, and also had to provide one rating when comparing the HWTS under consideration to each other.

Group indecision, with regard to rating, was inevitable when considering the background of our decision makers. The decision making group was comprised of end users, manufacturers of the HWTS, and the design team. The individuals in this group judged the criteria, and HWTS from different viewpoints, and this could not be accounted for by the crisp AHP model each individual ranking was averaged. The fuzzy model, on the other hand allowed for such indecision.

The ability of the fuzzy model to model group indecision lies in its flexibility. Each criterion was broken down into subsets, which were modelled by membership functions. The subsets of each criterion are determined by its domain. When subsets overlap, it showed that there is group indecision regarding whether a particular value fits in a subset. This indecision was modelled in the membership functions. Therefore, unlike the AHP models, where one must find the average outcomes of individual ratings in order to come to a uniform rating, the fuzzy model easily accepts indecision, thus allowing for a situation where one value can be seen from different viewpoints

The neural network component of the fuzzy model allows it to be used for any generic HWTS that is considered for deployment, provided that the particular HWTS has been analysed in terms of deployment cost, risk, accessibility, and production effectiveness criteria. Then, all one has to do is use the rules engine to determine where a HWTS is in terms of choice. The model can be easily extended if a criterion has been deemed important enough to be added to the list of current criteria, provided that one first goes through the exercise of fuzzifying this criterion. The neural network model was quite unforgiving when it came to the water treatment systems under consideration. The BSFZ was chosen as the best candidate for deployment even though it barely fell into the Low Preference (LP) category. The BSFZ was chosen as the best alternative using both the AHP and fuzzy neuro methodologies. The difference was that the fuzzy neuro model generalizes the selection of water treatment systems beyond those that were used in this project. This makes it usable in any situation where there are a multitude of alternative choices where only one can be chosen given defined criteria.

## 5.4 Conclusion

The decision making processes used to determine which water purification systems should be deployed at Makwane should not be taken lightly as it has wide ranging ramifications on the Makwane community. The decision making process, facilitated by AHP, helps to document the reasons behind the selection of particular criteria and alternative water purification systems. This is especially important in Africa where the selection and use of resources goes undocumented, but the effects of these unsound decisions are often felt community wide.

The BSFZ was chosen as the ideal water purification system to be deployed in Makwane Village because it has, on an aggregate level, satisfied the requirements of all four stated criteria necessary for the creation of a value chain that deploys household water purification systems in Africa.

The decision makers were not too enamoured with the deployment of a borehole system in the short term. The maintenance activities and skills needed to keep a borehole in operation was too costly. Furthermore, in a rural setting, with not enough people to watch over the borehole system, leaves it subject to vandalism and theft of materials. The implications for this on the village population are too high to ignore. It should be noted that systems such as the BSFZ and SIPP are a solution for the short to medium term, and in the long run a fully functioning, piped water purification and distribution system should be put in place.

The way the AHP model collates inconsistent information from individual decision makers creates an outcome that does not maximize value for end users. Therefore, the fuzzy neural network model adds a much needed layer to the decision making process as it willingly incorporates inconsistent decision making from decision makers. This model is essential in that it allows all voices to be heard and creates a more democratic process that takes into account the opinions of everyone involved in the decision process, thus adding value to the end users.

# Chapter 6

# Conclusion and Recommendations

## 6.1 Conclusion

Although Africa has made great strides in pursuing the millennium development goals (MDG), it fell short in some critical areas, one of them being the provision of clean water to African populations. Rural African populations in particular, have felt the brunt of the inability of African institutions to provide safe drinking water. Due to rapid urbanization in African countries, most resources have been steered towards the provision of services in urban areas, even though these services are rarely optimal.

In recent times, African institutions, as well as NGOs have begun to pursue the delivery of water purification systems in rural Africa. The deployment of these systems are often not successful in the medium term because those in charge often overlook the Africa specific criteria and processes that these systems must satisfy in order for them to operate optimally. This is why the central theme of this study was providing a standardized process for selecting the ideal water purification system in rural African villages.

There are several water purification systems available for deployment in Africa. These systems have been categorized into centralized and decentralized systems. Centralized systems are piped systems distributing water to a community from a central purification plant. Decentralized systems on the other hand, are smaller, and can be deployed directly to the home. Decentralized systems are also a lot cheaper to deploy. It is for these reasons that decentralized systems are the preferred system to deploy in rural areas of Africa such as Makwane Village. Through systematic analysis, three water treatment systems were identified for deployment in Makwane. They were called the Biosand Filter with Zeolites (BSFZ), the Silver Impregnated Porous Pot (SIPP), and a borehole system.

Makwane Village was reminiscent of the quintessential rural African village, characterised by low income households, with individuals having a low level of education. This is why Makwane was selected as the case study for the deployment of household decentralized water purification systems.

A thorough analysis of available literature, as well as questioning subject matter experts, allowed us to narrow four specific criteria that purification systems, and the supply chains that deploy them, must adhere to in order to for the purification systems to function optimally in rural areas. The four criteria were: deployment costs (affordability), reliability, social impact, and production effectiveness. Each criteria was analysed extensively to understand the impact it has on the deployment of water purification systems in Makwane Village.

The final part of the study centered on deciding which one of the three alternative water purification systems would be deployed in Makwane Village, and which decision making model was capable of facilitating the decision making process. Two variations of the Analytic Hierarchy Process (AHP) were used to facilitate the decision making process initially. Due to some shortcomings of the AHP models, a fuzzy neural network model was also used to help facilitate the decision making process. The decision makers finally settled on the BSFZ as the ideal candidate to be deployed in Makwane Village as it satisfied the requirements of all criteria.

## 6.2 Recommendations

Though Makwane village was chosen as the case study for this thesis, this author believes that the overall approach taken to identify the ideal water purification systems for Makwane can be extrapolated and used for all development projects in rural villages of Africa. This method provides a systematic and documented approach for decision making that is sorely missed in Africa. Its adoption could curtail the misuse of resources that has characterized the African continent since colonization.

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# Appendices

## Appendix A: Estimated Demand for clean Water in South Africa

| | Location | Households per district | Percentage households without piped water | Initial Estimated Demand in Households |
|---|---|---|---|---|
| 1 | Eastern Cape | 1665048 | 22.1% | 367976 |
| | Cacadu | 103295 | 3.6% | 3719 |
| | Amathole | 237776 | 30.0% | 71333 |
| | Chris Hani | 210852 | 13.3% | 28043 |
| | Joe Gqabi | 97775 | 25.8% | 25226 |
| | O.R. Thambo | 298229 | 51.0% | 152097 |
| | Alfred Nzo | 169261 | 49.8% | 84292 |
| | Buffalo City | 223568 | 2.5% | 5589 |
| | Nelson Mandela Bay | 324292 | 1.0% | 3243 |
| | | | | |
| 2 | Free State | 823316 | 2.2% | 18113 |
| | Xhariep | 45368 | 1.6% | 726 |
| | Lejweleputswa | 183163 | 2.0% | 3663 |
| | Thabo Mofutsanyane | 217884 | 3.2% | 6972 |
| | Fezile Dabi | 144980 | 1.1% | 1595 |
| | Mangaung | 231921 | 2.1% | 4870 |
| | | | | 0 |
| 3 | Mpumalanga | 1075488 | 12.6% | 135511 |
| | Gert Sibande | 273490 | 8.9% | 24341 |
| | Nkangala | 356911 | 7.3% | 26055 |
| | Ehlanzeni | 445087 | 19.0% | 84567 |
| | | | | |
| 4 | Limpopo | 1265483 | 14.0% | 177168 |
| | Mopani | 296320 | 15.8% | 46819 |
| | Vhembe | 335276 | 11.7% | 39227 |
| | Capricorn | 342838 | 10.8% | 37027 |
| | Waterberg | 179886 | 5.7% | 10254 |
| | Greater-Sekhukhune | 263802 | 24.8% | 65423 |
| 5 | Western Cape | 1633901 | 0.9% | 14705 |
| | West Coast | 106781 | 1.0% | 1068 |
| | Cape Winelands | 198165 | 0.8% | 1585 |
| | Overberg | 77196 | 0.8% | 618 |
| | Eden | 164110 | 2.2% | 3610 |
| | Central Karoo | 19076 | 0.6% | 114 |
| | City of Cape Town | 1068573 | 0.7% | 7480 |

| | | | | |
|---|---|---|---|---|
| 6 | Gauteng | 3909022 | 1.8% | 70362 |
| | Sedibeng | 279768 | 1.0% | 2798 |
| | West Rand | 267397 | 2.0% | 5348 |
| | Ekurhuleni | 1015465 | 1.1% | 11170 |
| | City of Johannesburg | 1434856 | 1.4% | 20088 |
| | City Tshwane | 911536 | 3.4% | 30992 |
| | | | | |
| 7 | Kwazulu-Natal | 981572 | 14.1% | 138402 |
| | Ugu | 179440 | 16.6% | 29787 |
| | Umgungundlovu | 272666 | 8.9% | 24267 |
| | Uthukela | 147286 | 20.2% | 29752 |
| | Umzinyathi | 113469 | 34.1% | 38693 |
| | Amajuba | 110963 | 7.7% | 8544 |
| | Zululand | 157748 | 30.7% | 48429 |
| | | | | |
| 8 | North West | 1062014 | 8.4% | 89209 |
| | Bojanala | 501696 | 9.7% | 48665 |
| | Ngaka Modiri Molema | 227001 | 13.9% | 31553 |
| | Dr Ruth Segomotsi Mompati | 125270 | 4.4% | 5512 |
| | Dr Kenneth Kaunda | 208047 | 1.6% | 3329 |
| | | | | |
| 9 | Northern Cape | 301406 | 2.6% | 7837 |
| | Namakwa | 33856 | 2.4% | 813 |
| | Pixleyka Seme | 49193 | 2.4% | 1181 |
| | Siyanda | 61097 | 2.3% | 1405 |
| | Frances Baard | 95929 | 2.5% | 2398 |
| | John Taolo Gaetsewe | 61331 | 3.9% | 2392 |

# Appendix B: Process Maps

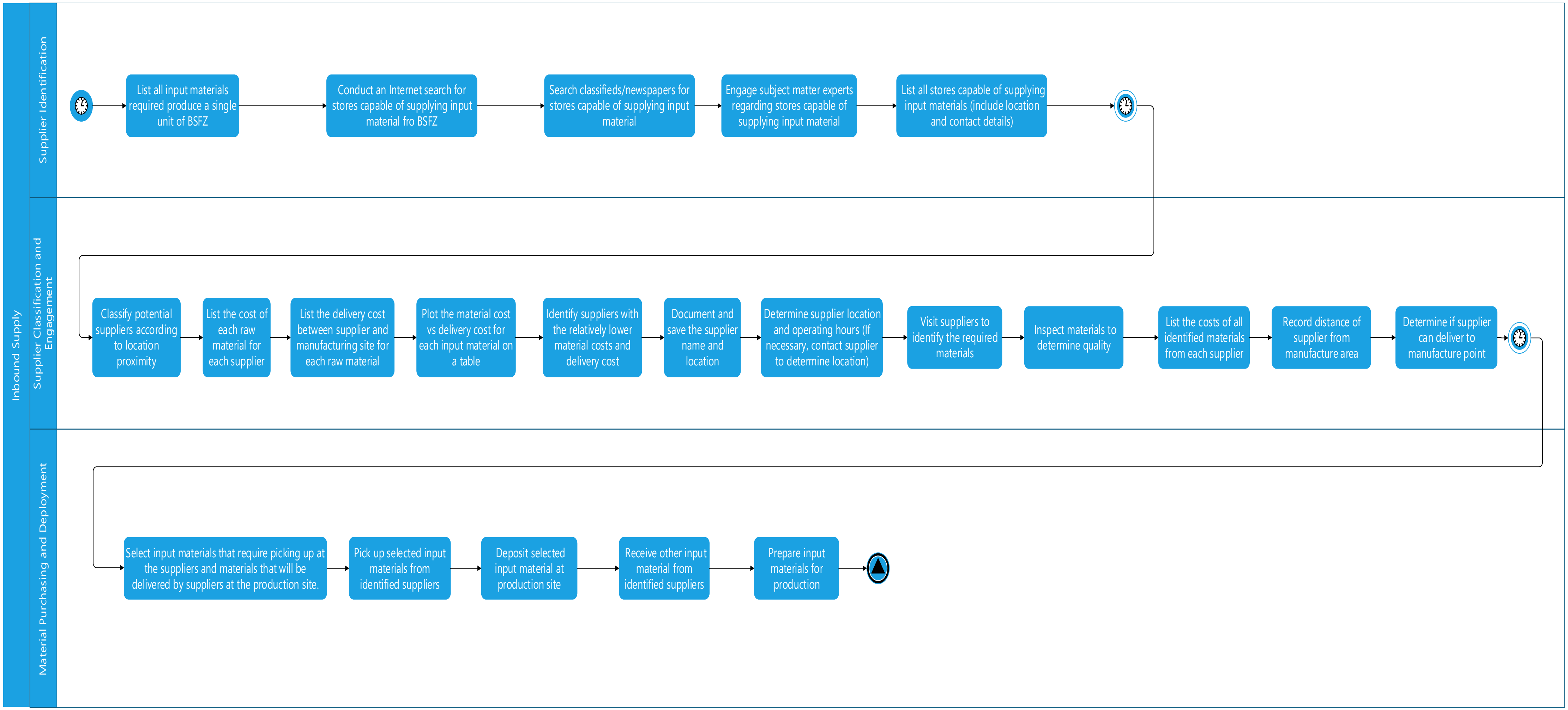

*Figure 4.1: Inbound Supply (SIPP and BSFZ)*

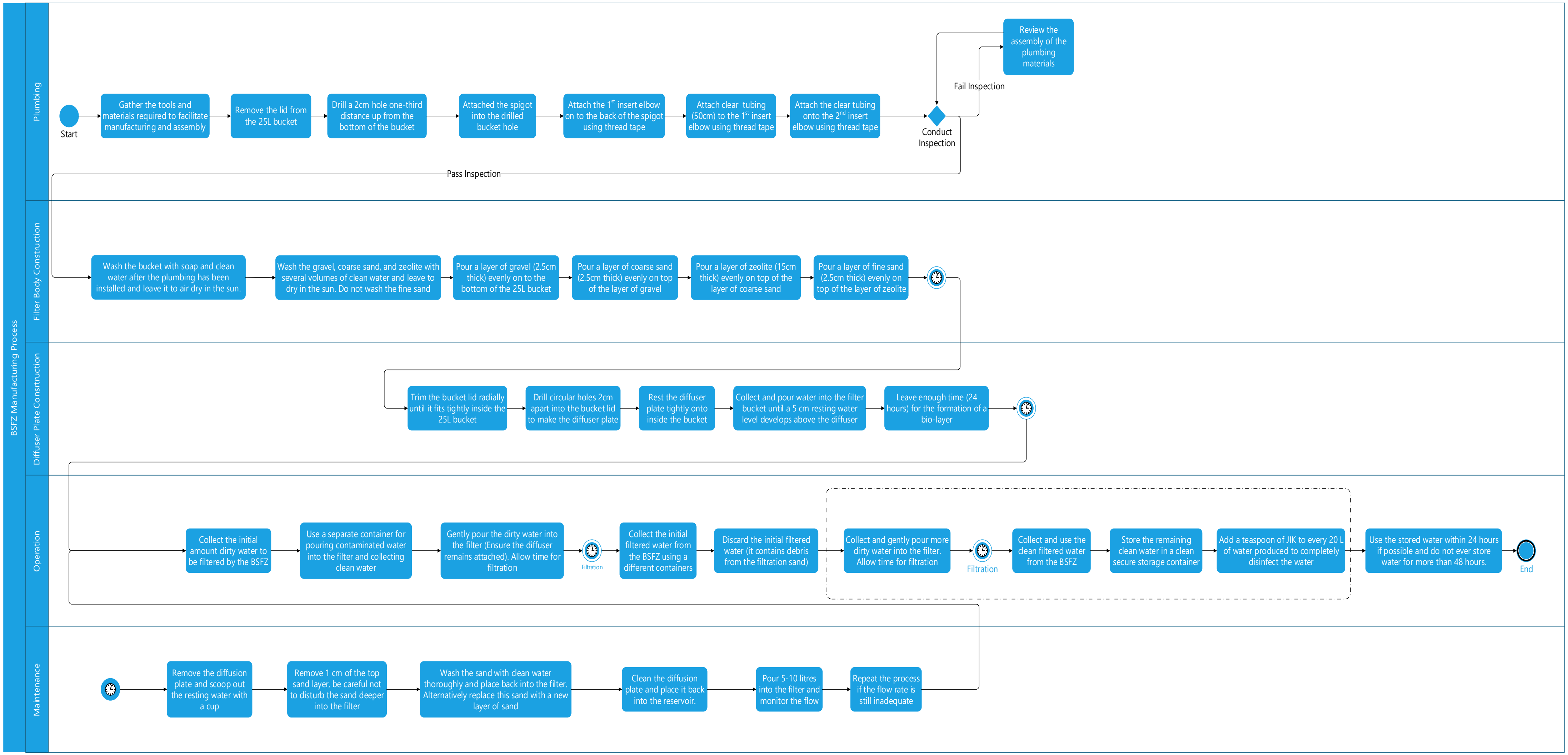

*Figure 4.2 Manufacture Operations and Maintenance of the BSFZ System*

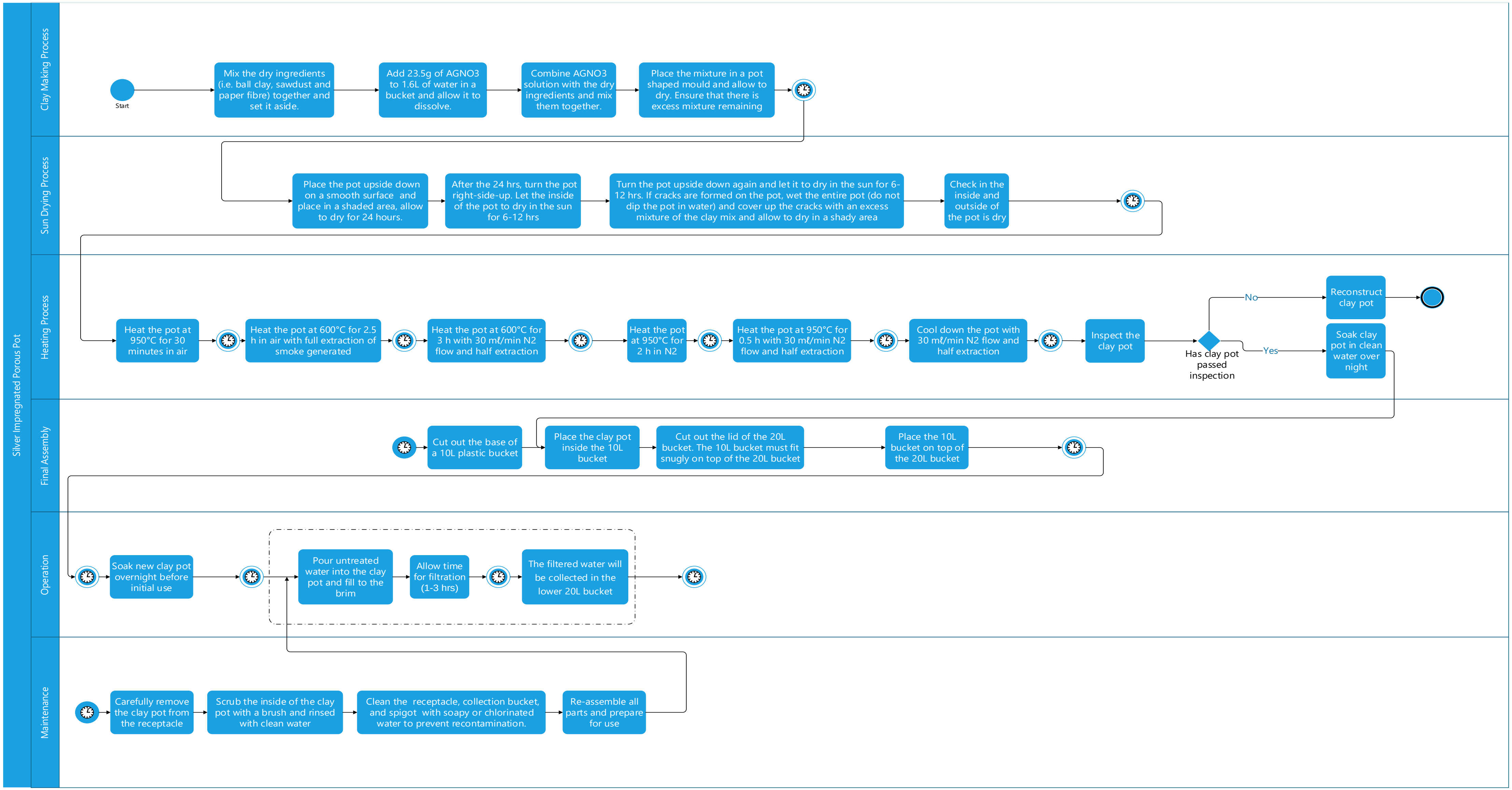

*Figure 4.11: Manufacture Operation and Maintenance of the SIPP System*

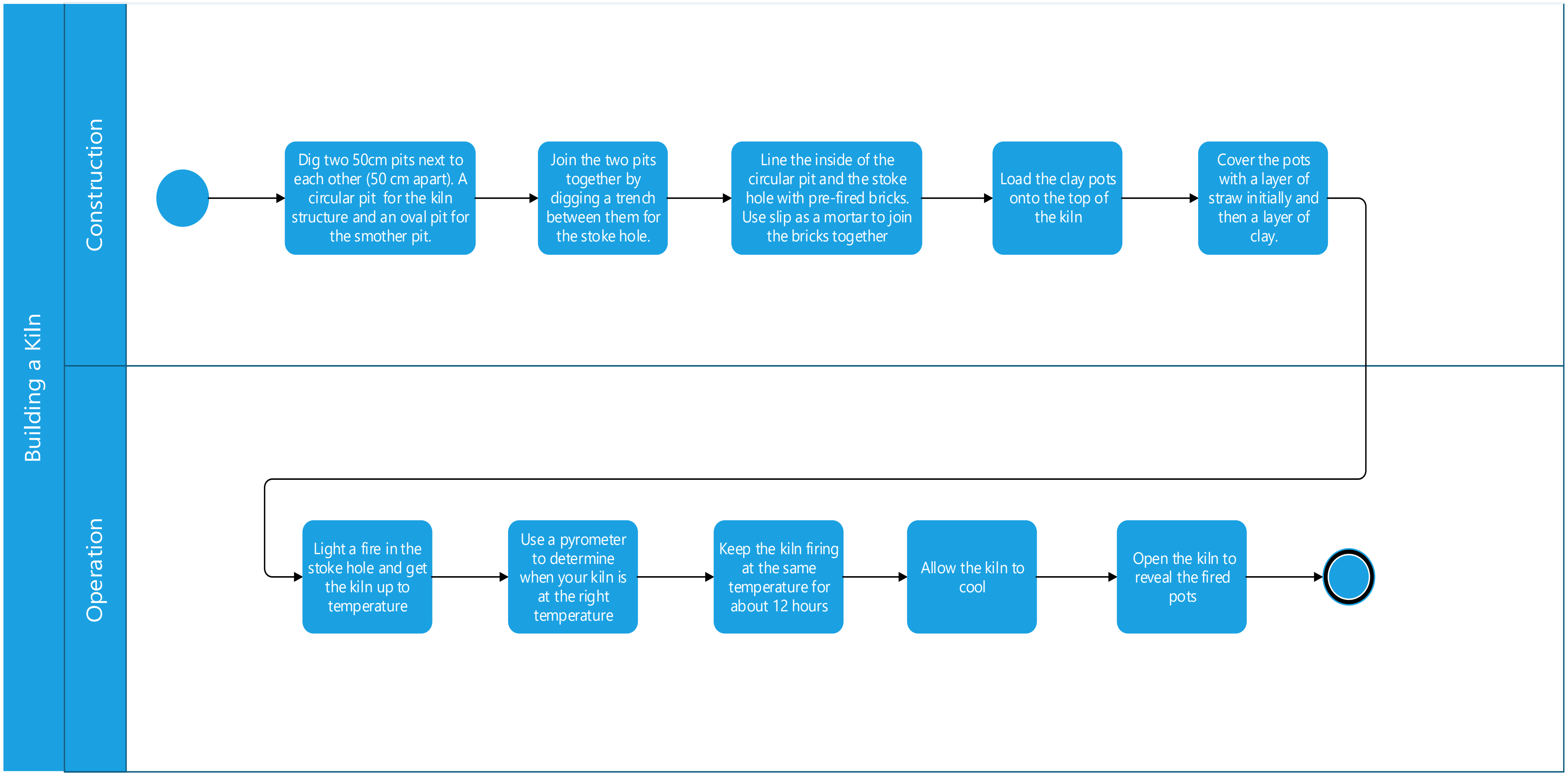

*Figure 4.26: Construction and Operation of a Kiln*

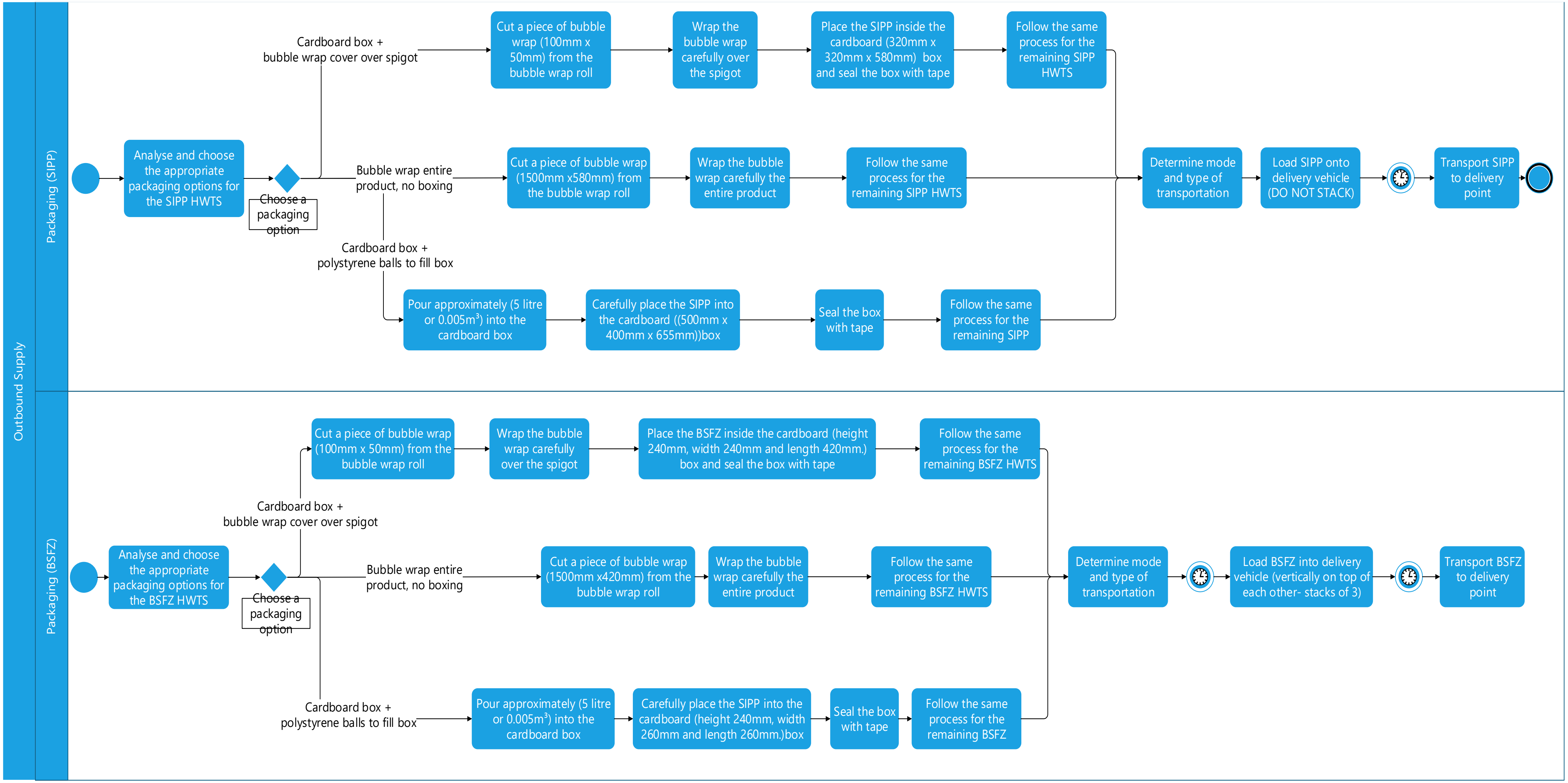

*Figure 4.19: Outbound Supply and Deployment of the SIPP and BSFZ System*

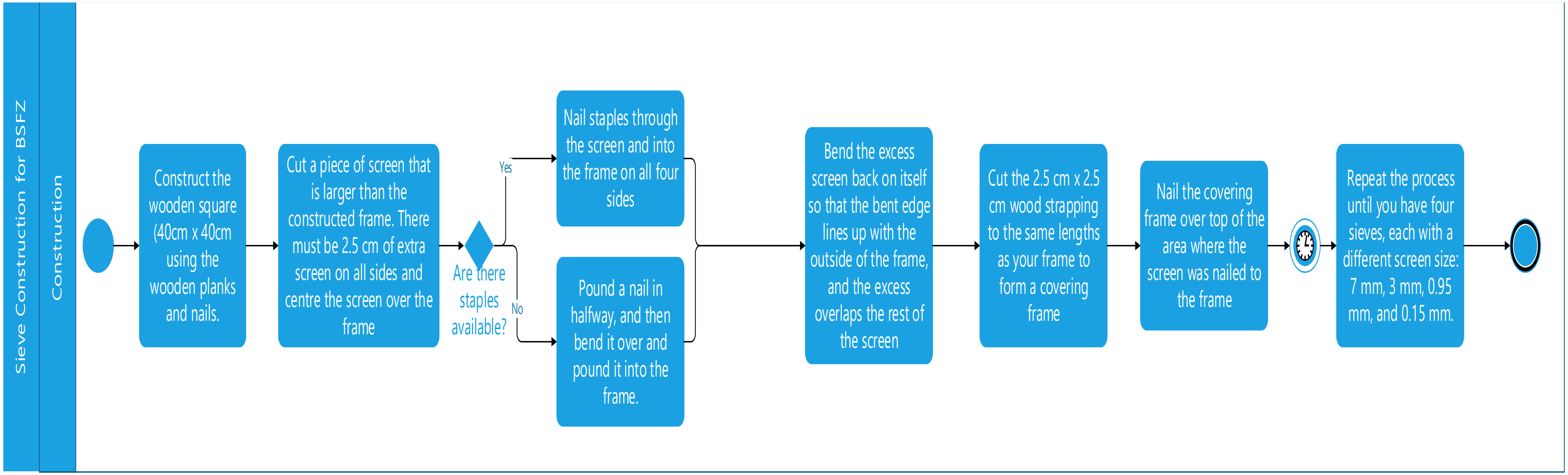

*Figure 4.10: Construction of a Sieve*

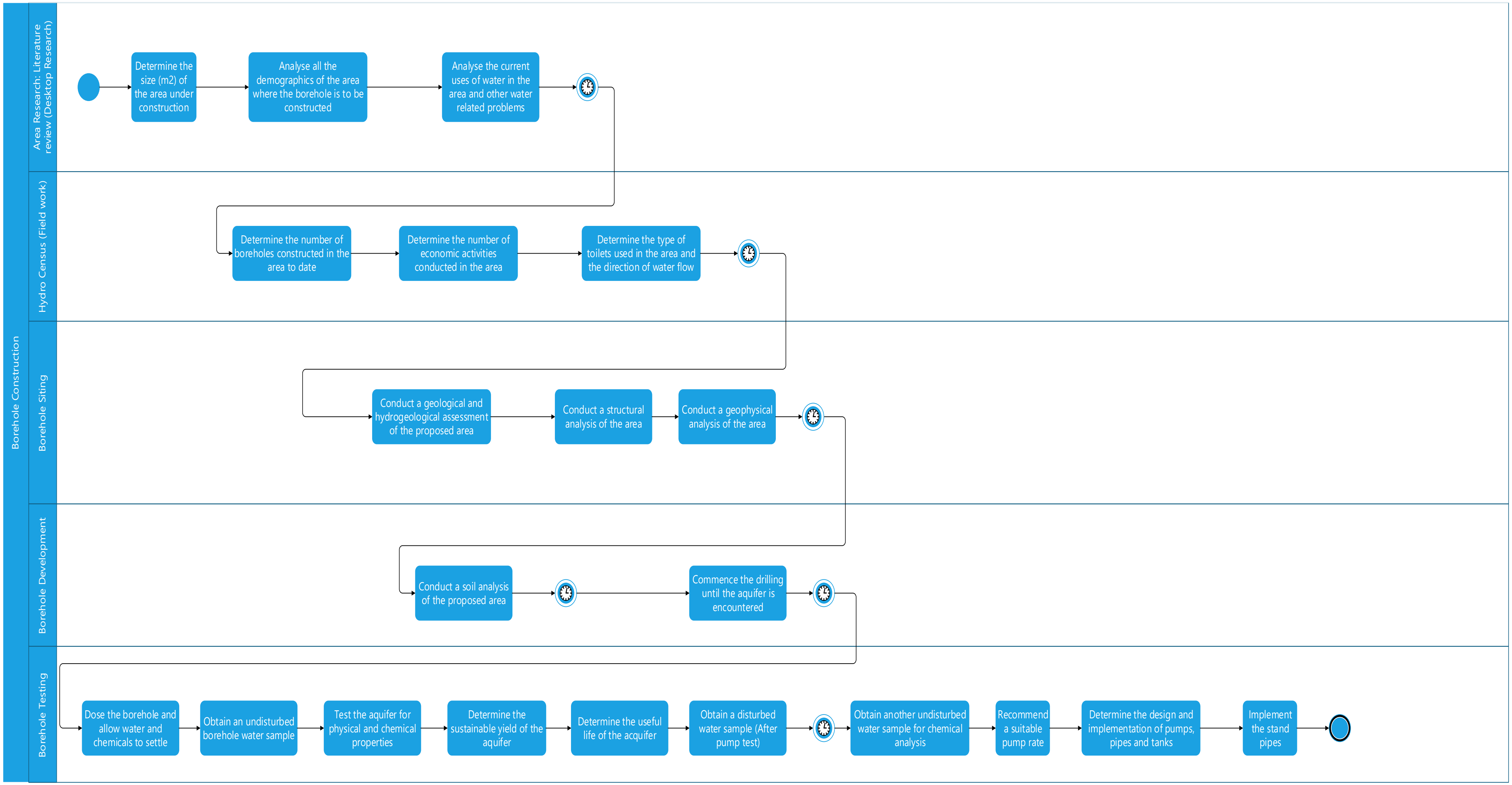

*Figure 4.20: Borehole Construction*

## Appendix C: Questionnaires

Questionairre 1

**Product Design**

1. What are the Design specifications?
2. Cost of Materials
3. Who does the design team consist of (names and qualifications)?
4. What are the material specifications?
5. What is the design process (end to end) and process statistics?
    - Functional Breakdown of design team including responsibilities.
    - Function sequencing
    - Activity breakdown of each function (BPMN)
    - Standard operating Procedures (SOP)
    - Total design process time including testing (end to end)
    - Design costs
    - Sourcing time per material
    - Instalation/assembly time
    - Testing Procedure
6. Which Design process step presents the greatest bottleneck (with regard to time)?
7. What is the products life cycle time? how was this derived?
8. Which parts are most susceptible to breakage
    - How often do these parts need to be replaced
    - What is the total cost of replacing such parts
    - What is the time taken to replace broken parts
9. What are the product/water quality testing process steps?
    - Cycle time for water quality testing
    - Costs associated with water quality testing
10. Which parts are most difficult to source

**Inbound Supply (Logistics)**

1. Who do you source from?
    - Company name
    - Type of material sourced
    - Address
    - Contact person
    - GPS location
    - Do they deliver?
    - Where do/would they deliver the material
    - OFCT (order fulfilment cycle time)
    - Delivery Costs(aggregate delivery costs and unit delivery costs)
    - Supplier capacity to respond to varying demand (maximum and minimum number of materials that can be delivered)
    - Number of broken/defective materials delivered
    - Delivery process costs
    - Delivery location

2. What is the inbound supply/delivery process Steps including statistics
    - Functional breakdown inbound supply procedures (purchasing, transfer, delivery process)
    - Functional sequencing
    - Activity Breakdown of each function (BPMN)
    - Standard operating Procedures (SOP)
    - Process cycle time
    - Possibilities for skills transfer
3. The percentage of orders meeting delivery performance with complete and accurate documentation and no delivery damage (perfect order fulfilment)
    - % delivery on commit date
    - % products delivered in perfect condition

## Manufacturing/Operations

1. What are the manufacturing process steps and process statistics?
   - Functional breakdown of manufacturing operations including responsibilities
   - Function sequencing
   - Activity Breakdown of each function (BPMN)
   - Standard Operating Procedures (SOP)
   - Activity/function cycle times
   - What are the different skills required for manufacturing.
   - Is there a training manual for manufacturing
   - Length of training
   - Cost of training
2. % defects per manufactured batch.
3. Manufacturing process risk (% risk, how often does equipment breakdown per cycle)
4. Cost of manufacturing 1 unit/1 batch.
   - Cost breakdown structure( Cost categories)
5. Cost of equipment used to manufacture products
6. Cost of materials used to manufacture products
7. Labour costs
8. Total Manufacturing cycle time
9. Where does manufacturing occur?
   - Location
   - Company name
   - Contact person
10. What is the manufacturing lead time
11. Is there a potential temporary storage facility at the manufacturing plant?
12. What are the maintenance activities (sequential and functional breakdown)
13. What are the skills required for maintenance

**Distribution (Outbound Logistics)**

1. Who are the potential distributors?
    - Location
    - Company name
    - Contact person

2. What are the distribution process steps and process statistics?
    - Functional breakdown of distribution operations of each distributor including responsibilities.
    - Function sequencing
    - Activity Breakdown of each function (BPMN)
    - Standard Operating Procedures (SOP)
    - Process cycle time (Order Fulfilment cycle time)
    - Process costs
    - Skills requirements for distribution
3. Distributor storage capacity, cost of storage?
4. The percentage of orders meeting delivery performance with complete and accurate documentation and no delivery damage (perfect order fulfilment)
    - % products delivered on commit date
    - % products delivered in perfect condition
5. Delivery Costs

**Point of Service**

1. What are the service process steps and process statistics?
    - Functional breakdown for the servicing of the community including responsibilities
    - Function sequencing
    - Activity Breakdown of each function (BPMN)
    - Standard Operating Procedures (SOP)
    - Process time (maintenance and distribution)

2. Potential Location of Point of Service (distribution and maintenance)
    - Location
    - Address

- GPS

3. Who will operate and maintain the point of service (skills required for operating point of service)
4. Required costs for operation and maintenance

**Stand Pipe Systems**

1. What are process steps used to deliver a fully functioning standpipe systems including statistics?
   - Functional breakdown of process steps including responsibilities
   - Function sequencing (VSM)
   - Activity Breakdown of each function (BPMN)
   - Standard Operating Procedures (SOP)
   - Cycle time (The time taken to construct a standpipe system)
   - Costs of building and implementation
2. Who are the potential stand pipe constructors
3. List of equipment used to construct a standpipe system
4. List of technical skills required to construct a standpipe system
5. What skills are required to maintain a stand pipe system
6. What is the total cost of maintaining a standpipe system
7. Potential Location of Standpipe systems

**Makwane Village Specs**

1. Village location (GPS)
2. Population Numbers
3. Population demographic Breakdown
4. Number of households (define households)
5. Map/Grid
6. Average number of people in the household
7. Water requirements per person and per household
8. Which Municipality services Makwane
9. Income generation avenues of inhabitants
10. GDP per capita of area
11. General level of education

Questionnaire 2

The following questions are intended for the human resources involved design, construction and maintenance of boreholes and standpipe systems.

**1. What is your current profession?**

**2. List your work experience.**

**3. Which industry do you currently work in?**

**4. How long have you been working in the above mentioned industry.**

## Stand Pipe Systems

What is the process steps used to deliver fully functioning standpipe systems including statistics?
What is the functional breakdown of process steps including responsibilities
What is the sequence of functions (VSM)
What us the activity Breakdown of each function (BPMN)
What are the standard Operating Procedures (SOP)
What is the Cycle time (The time taken to construct a standpipe system)
What are the costs of building and implementation
Who are the potential stand pipe constructors
List of equipment used to construct a standpipe system
List of technical skills required to construct a standpipe system
What skills are required to maintain a stand pipe system
What is the total cost to build and maintain a standpipe system
Potential Location of Standpipe systems

## *Questionnaire 3*

The following questions are intended for the human resources involved in servicing the community with regard to household water purification systems

## DEMOGRAPHIC QUESTIONS

**1. How long have you been working in the above mentioned industry.**

## Point of Service

What are the service process steps and process statistics?
What is the functional breakdown for the servicing of the community including responsibilities

what is the sequence of functions
What is the activity breakdown of each function (BPMN)
What are the Standard Operating Procedures (SOP)
What is the process cycle time (maintenance and distribution)

Potential Location of Point of Service (distribution and maintenance)
Location
Address
GPS
Who will operate and maintain the point of service (skills required for operating point of service)

What are the required costs for operation and maintenance

## ***Questionaire 3***

**Makwane Village Questionnaire**
*Please circle the appropriate box*
**1. How many people live in your household?**
**2. Did you know what a water purifier was before this conversation?**
Yes
No
**3. Has anyone in your household been sick due to contaminated water in the last month?**

## BACKGROUND OF PURIFIED WATER USAGE

**4. On a scale of 1 to 5 (One being very clean and 5 being very dirty) how do you perceive your water quality at the source?**
**5. Have you ever treated water using water treatment devices or a chemical agent? Which agent?**
**6. How well do you know about water purification devices?**
**7. What has your experience been so far? (Open –ended)**
Excellent
Good
Bad
**8. How often do you purify water per week?**
Once a week
Twice a week
Three time a week
More than 3 times per week

**9. How do you purify your water?**
Boiling
Salts
Sunlight
Bleach
Chemical agent
Other (Please specify)

**10. How often do you purify water per week, what is it used for?**

| | Never | Rarely | Often | Always |
|---|---|---|---|---|
| Drinking | | | | |
| Washing | | | | |
| Bathing | | | | |

**11. What is the weekly volume of purified water?**

**12. Where do you mostly access your drinking water (Water source)?**
River
Municipal tap
Rain Tank
Natural Spring/borehole
Other (Please specify)

**13. What steps do you use to collect water (process flow)?**
**14. How much time does it take to collect water?**
Less than 30 min
Between 30 min and 1 hour
Between 1 and 2 hours
Over 2 hours
**15. Are you comfortable collecting water using the above mentioned steps?**
Yes
No
Indifferent
If not, what is it about collecting water using the afore mentioaned steps that make you unconfortable

**16. How much do you spend on water purification per month on average?**
Less than R50
Between R50 and R100
Between R100and R200
More than R200

**17. How would you rate your knowledge about water purification devices?**
None
Little
Moderate
High

**18. Why do you use water purification devices?**
To Avoid contamination/preserve health
It is Easier than collecting municipal water
other
**19. How did you find out about the importance of using water purification devices, how did you learn this technique?**

| | | How did you find out about the importance of purification devices | | | | |
|---|---|---|---|---|---|---|
| | | Peers | Family and friends | Neighbours | Municipality | Other |
| Who taught you the technique? | Peers | | | | | |
| | Family and friends | | | | | |
| | Neighbours | | | | | |
| | Municipality | | | | | |
| | Other | | | | | |

**If other, please specify who**

## Appendix D: Cost Models

*Table 4.25: The BSFZ Cost Model Extended Over 10 Years*

| **Material Costs** | **Amount** |
|---|---|
| 120 units of BSFZ | R 16 347.78 |
| 20 units (spare parts) for BSFZ | R 2 724.63 |
| **Labour** | |
| Once off | R 16 390.44 |
| Maintenance | R 2 731.74 |
| **Equipment** | R 934.00 |
| Transportation (inbound) | R 870.48 |
| Total Implementation Costs - year 1 | R 39 999.07 |
| **Annual Replenishment and Production Costs Increased at 10% year on year** | |
| Total implementation Costs - Year 2 | R 41 999.02 |
| Total Implementation Costs - Year 3 | R 44 098.97 |
| Total implementation Costs - Year 4 | R 46 303.92 |
| Total implementation costs - Year 5 | R 48 619.12 |
| Total Implementation costs - Year 6 | R 51 050.08 |
| Total Implementation Costs - Year 7 | R 53 602.58 |
| Total Implementation Costs - Year 8 | R 56 282.71 |
| Total Implementation Costs - Year 9 | R 59 096.84 |
| Total Implementation Costs - Year 10 | R 62 051.69 |

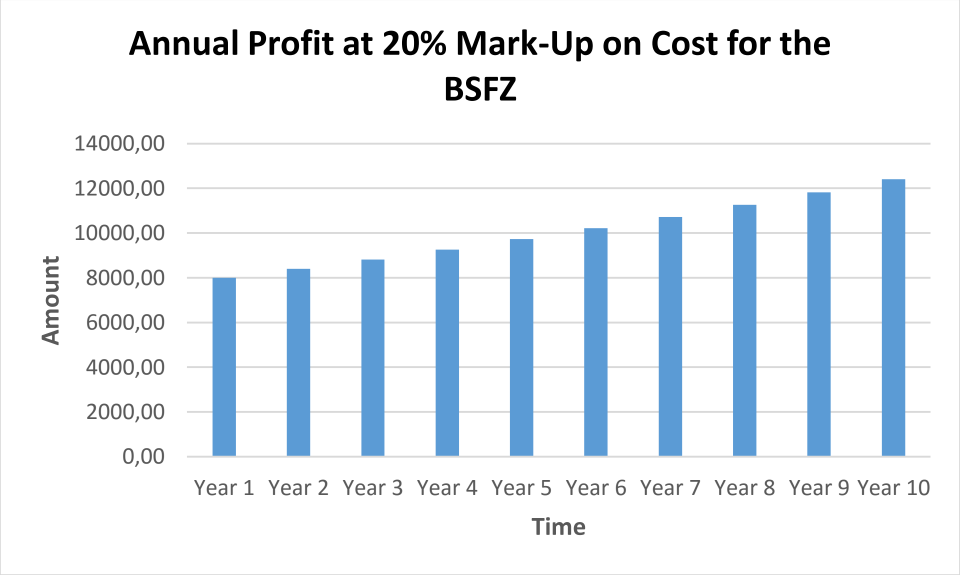

*Figure 4.21: Annual Profit at 20% Mark Up on Cost for the BSFZ*

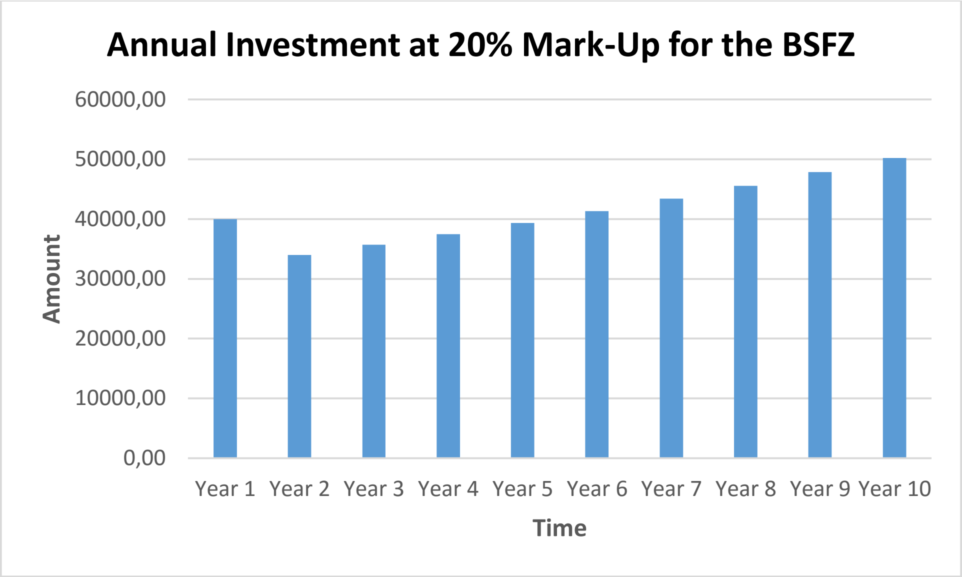

*Figure 4.22: Annual Investment at 20% Mark Up on Cost for the BSFZ*

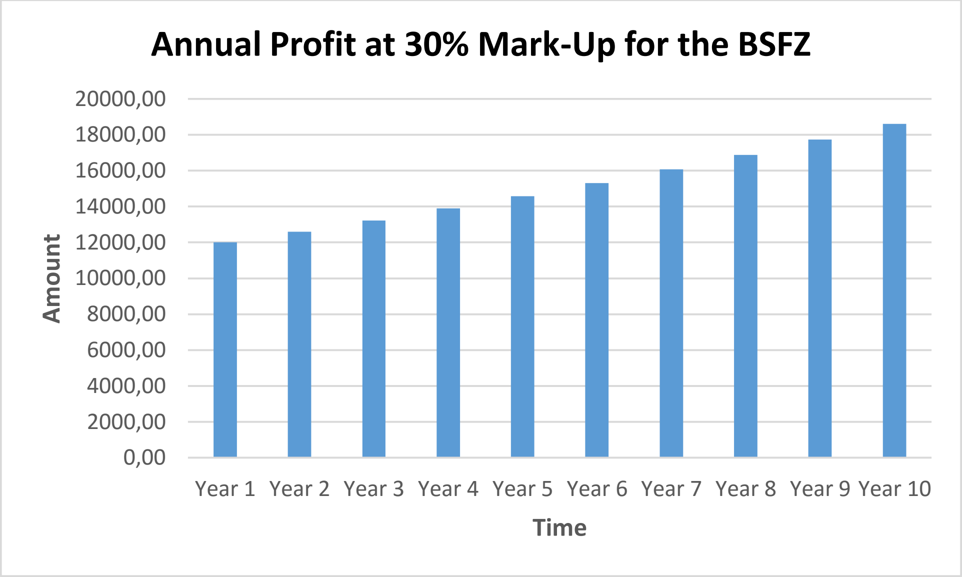

*Figure 4.23: Annual Profit at 30% Mark-Up for the BSFZ*

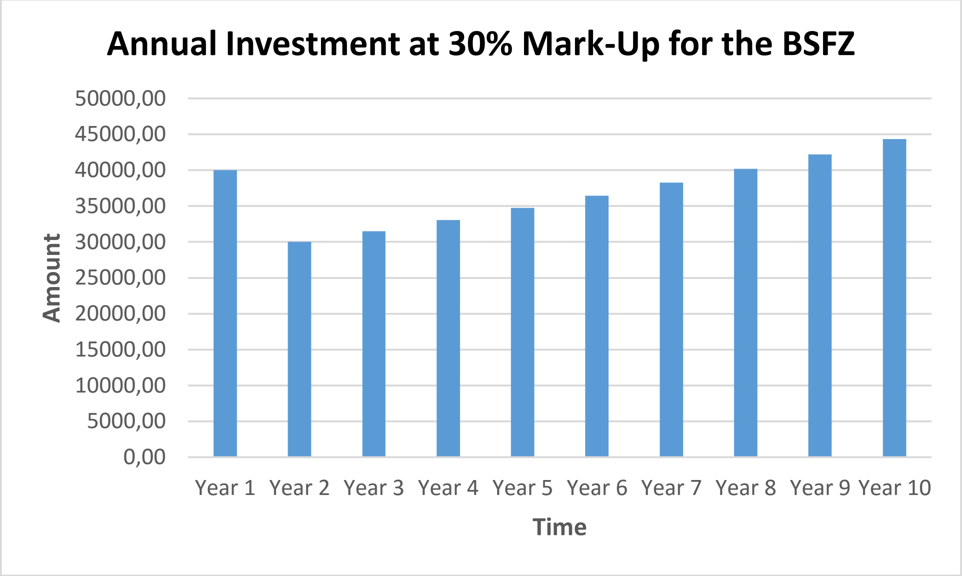

*Figure 4.24: Annual Investment at 30% Mark-Up for the BSFZ*

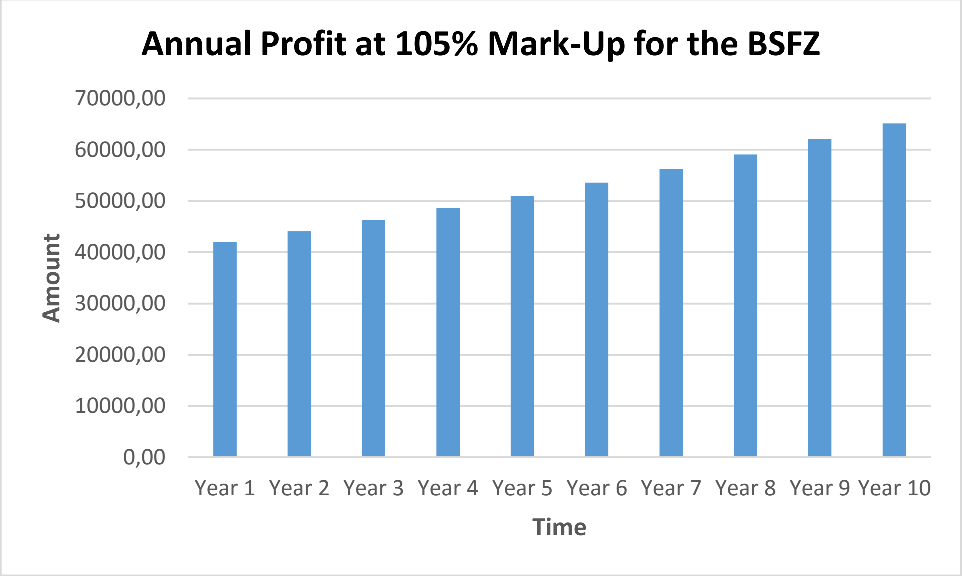

*Figure 4.25: Annual Profit at 105% Mark-Up for the BSFZ*

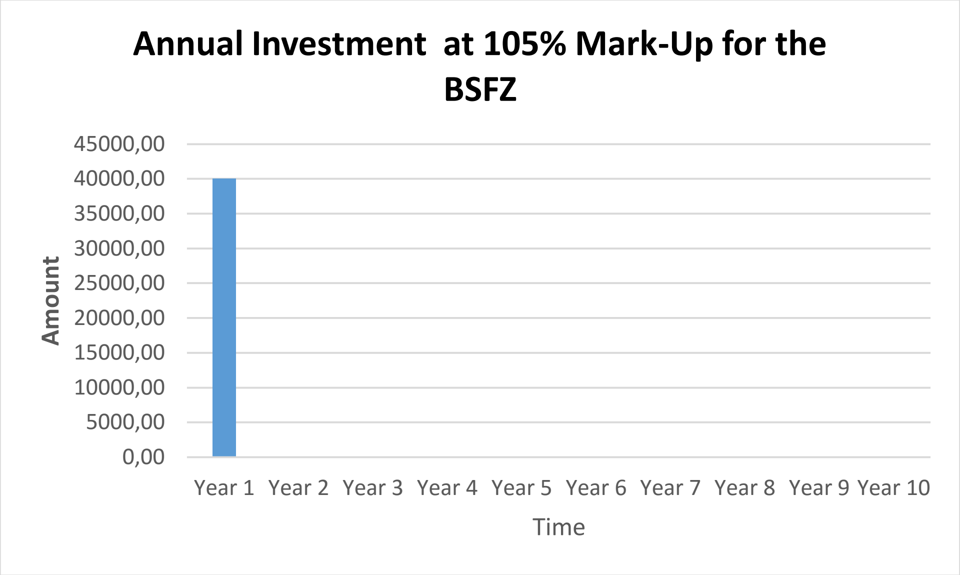

*Figure 4.26: Annual Investment at 105% Mark-Up for the BSFZ*

*Table 4.26: The SIPP Cost Model Extended Over 10 Years*

| **Material Costs** | |
|---|---|
| 120 units | R 35 415.34 |
| 20 units (spare parts) | R 5 902.56 |
| **Labour** | |
| once off | R 16 390.44 |
| Maintenance | R 2 731.74 |
| **Equipment** | R 934 |
| Kiln Construction | R 4 991 |
| **Transportation (inbound)** | R 631.10 |
| Total implementation costs - year 1 | R 66 995.95 |
| **Annual replenishment and production costs** | |
| Total implementation Costs - year 2 | R 73 695.55 |
| Total implementation Costs - year 3 | R 81 065.10 |
| Total implementation Costs - year 4 | R 89 171.61 |
| Total implementation Costs - year 5 | R 98 088.77 |
| Total implementation Costs - year 6 | R 107 897.65 |
| Total implementation Costs - year 7 | R 118 687.41 |
| Total implementation Costs - year 8 | R 130 556.15 |
| Total implementation Costs - year 9 | R 143 611.77 |
| Total implementation Costs - year 10 | R 157 972.95 |

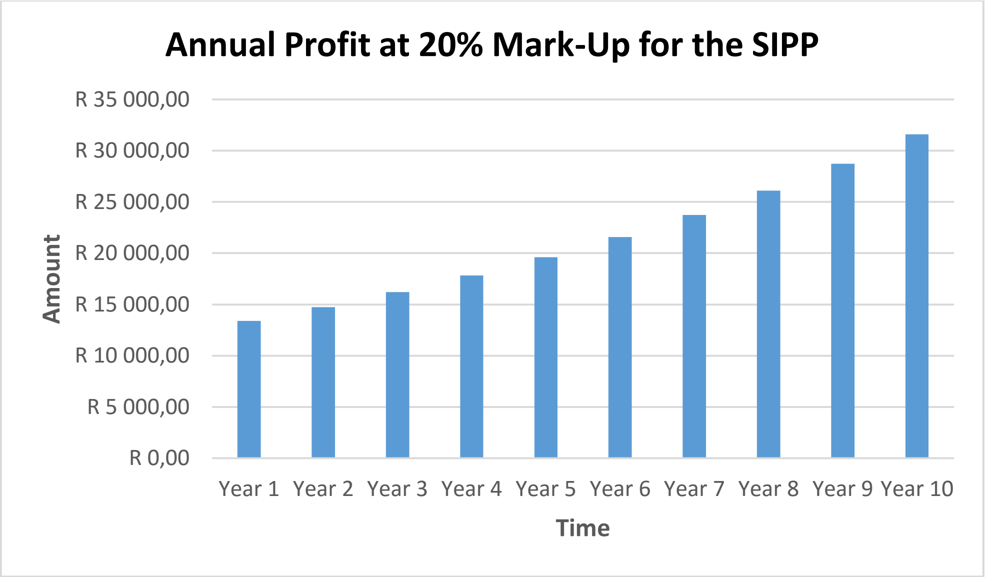

*Figure 4.27: Annual profit at 20% Mark-Up for the SIPP*

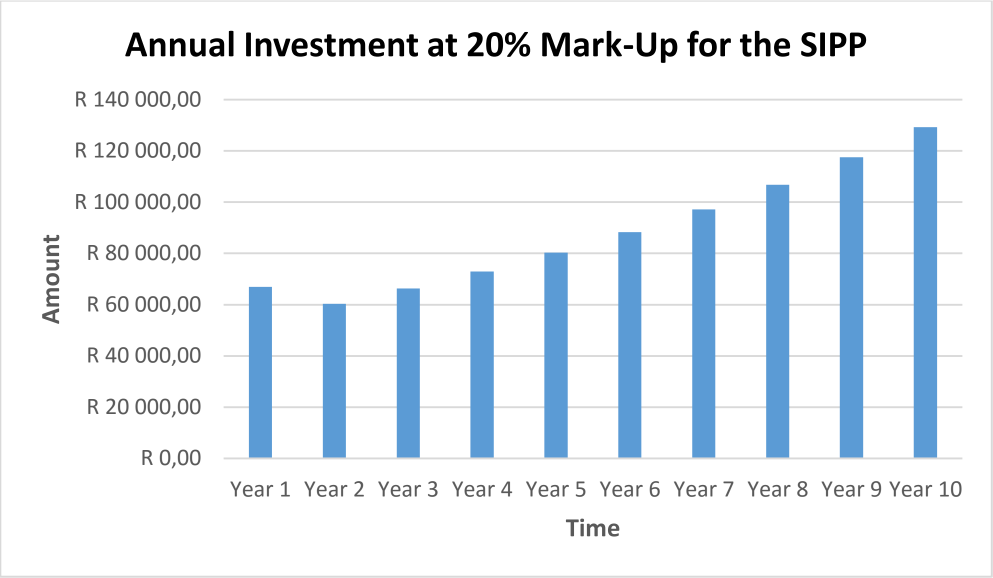

*Figure 4.28: Annual Investment at 20% Mark-Up for the SIPP*

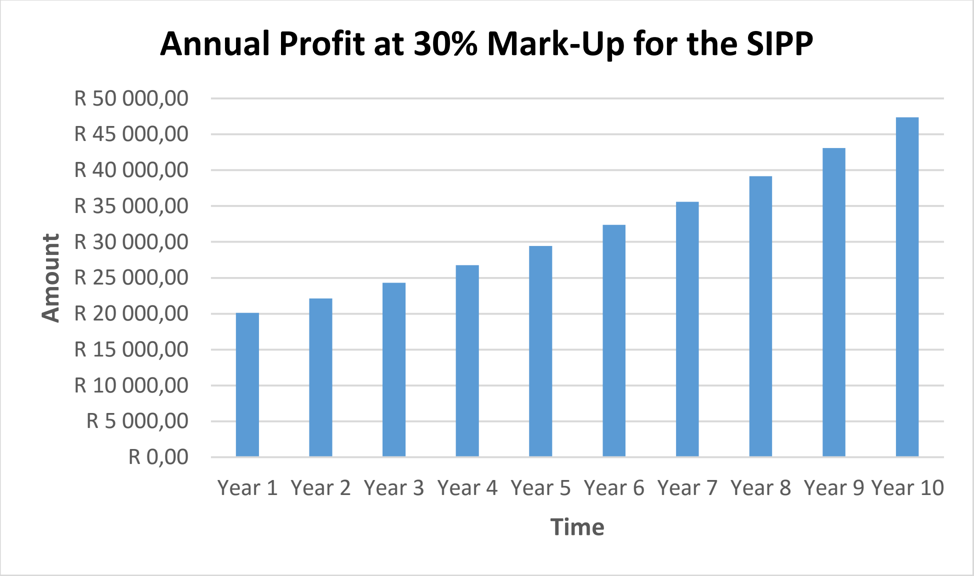

*Figure 4.29: Annual Profit at 30% Mark-Up for the SIPP*

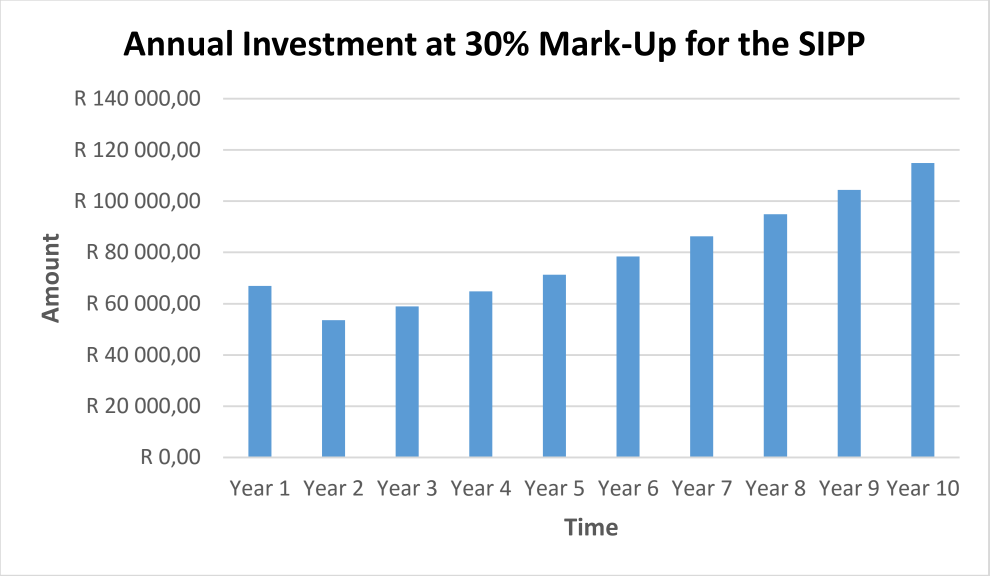

*Figure 4.30: Annual Investment at 30% Mark-Up for the SIPP*

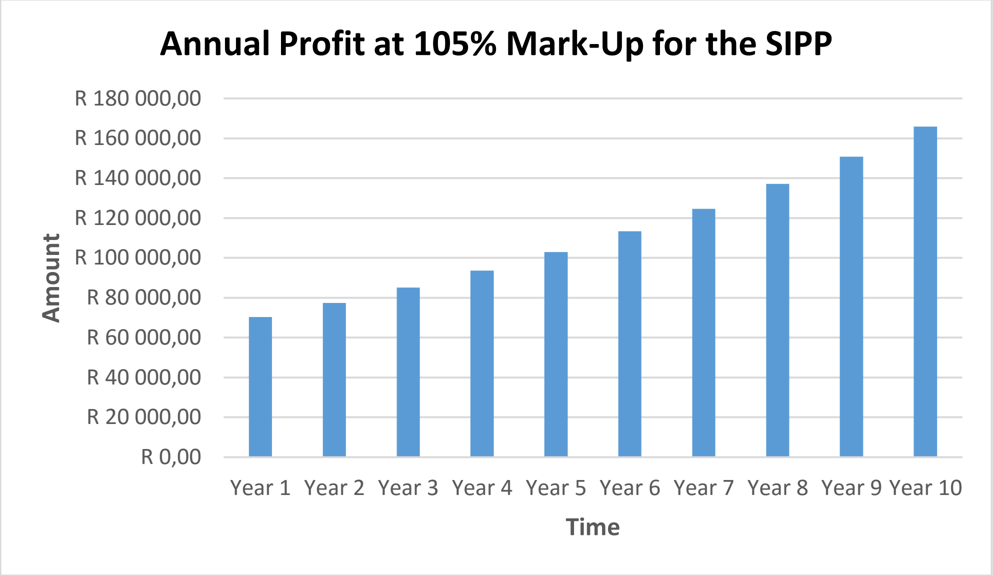

*Figure 4.31: Annual Profit at 105% Mark-Up for the SIPP*

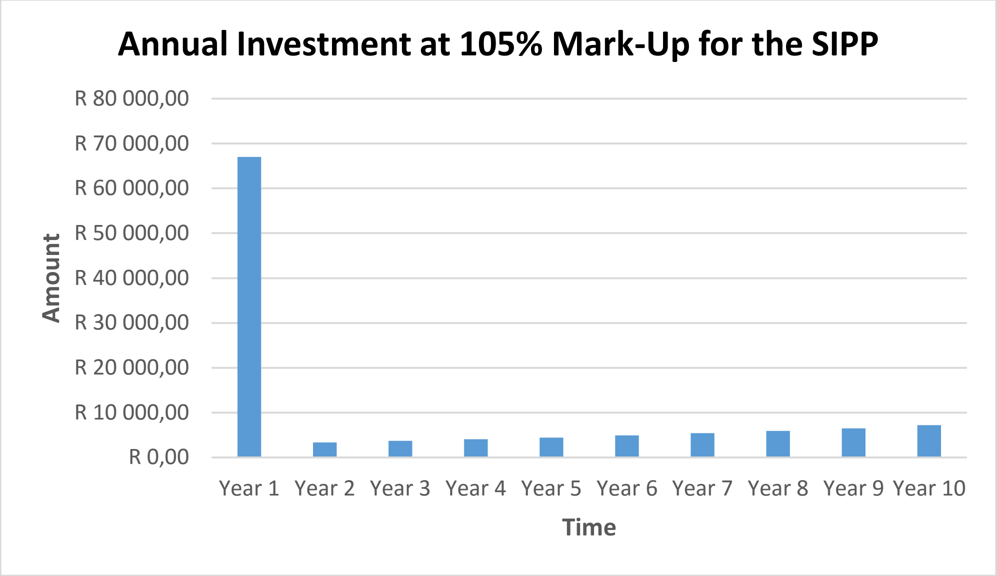

*Figure 4.32: Annual Investment at 30% Mark-Up for the SIPP*

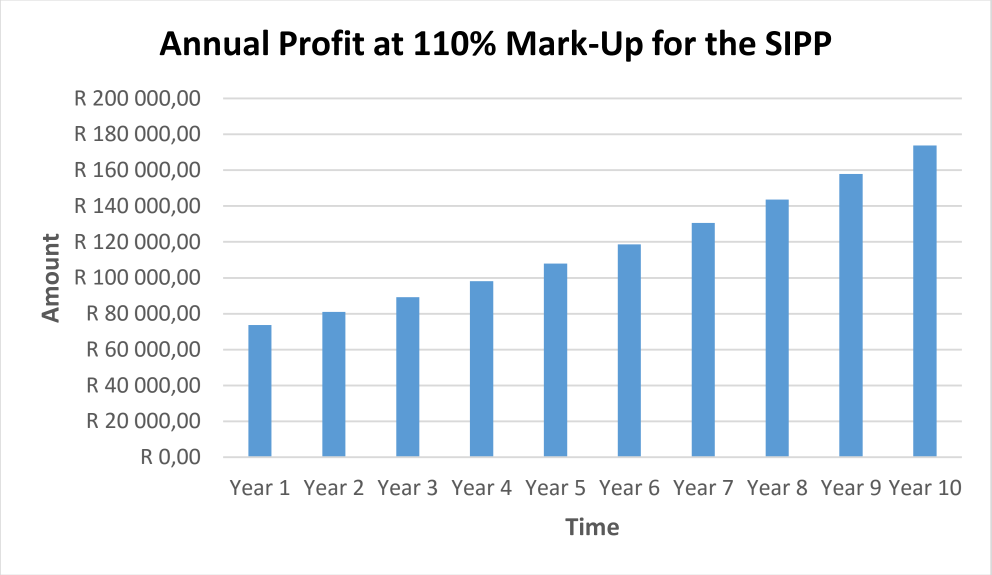

*Figure 4.33: Annual Profit at 110% Mark-Up for the SIPP*

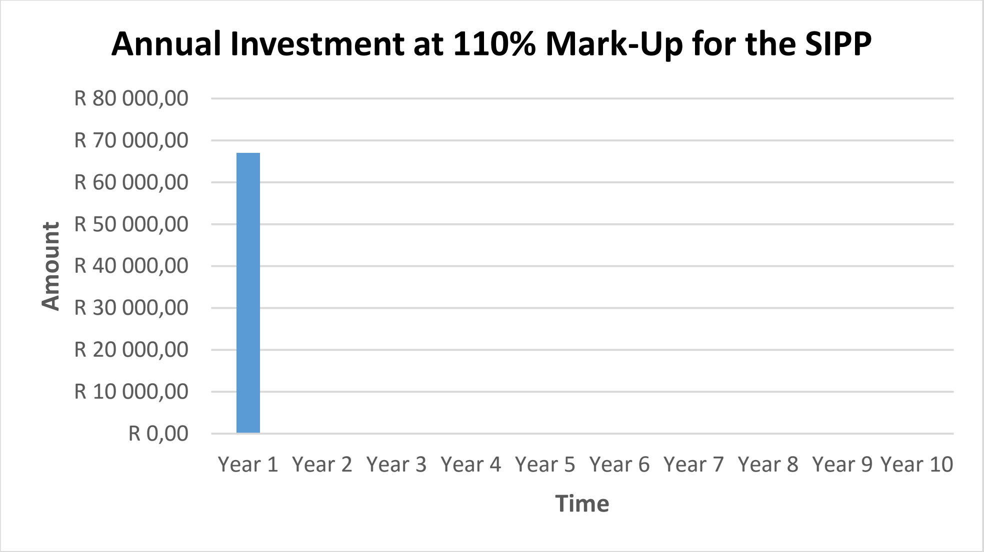

*Figure 4.34: Annual Investment at 110% Mark-Up for the SIPP*

## Appendix E: Rules Engine of the Neural Network Model

1. If cost is inexpensive and Risk is unreliable and Distance is very close and flow rate is low then criteria is output 1mf1
2. If cost is inexpensive and Risk is unreliable and Distance is very close and flow rate is acceptable then criteria is output 1mf2
3. If cost is inexpensive and Risk is unreliable and Distance is very close and flow rate is high then criteria is output 1mf3
4. If cost is inexpensive and Risk is unreliable and Distance is very close and flow rate is very high then criteria is output 1mf4
5. If cost is inexpensive and Risk is unreliable and Distance is close and flow rate is low then criteria is output 1mf5
6. If cost is inexpensive and Risk is unreliable and Distance is close and flow rate is acceptable then criteria is output 1mf6
7. If cost is inexpensive and Risk is unreliable and Distance is close and flow rate is high then criteria is output 1mf7
8. If cost is inexpensive and Risk is unreliable and Distance is close and flow rate is very high then criteria is output 1mf8
9. If cost is inexpensive and Risk is unreliable and Distance is moderately far and flow rate is low then criteria is output 1mf9
10. If cost is inexpensive and Risk is unreliable and Distance is moderately far and flow rate is acceptable then criteria is output 1mf10
11. If cost is inexpensive and Risk is unreliable and Distance is moderately far and flow rate is high then criteria is output 1mf11
12. If cost is inexpensive and Risk is unreliable and Distance is moderately far and flow rate is very high then criteria is output 1mf12
13. If cost is inexpensive and Risk is unreliable and Distance is far and flow rate is low then criteria is output 1mf13
14. If cost is inexpensive and Risk is unreliable and Distance is far and flow rate is acceptable then criteria is output 1mf14
15. If cost is inexpensive and Risk is unreliable and Distance is far and flow rate is high then criteria is output 1mf15
16. If cost is inexpensive and Risk is unreliable and Distance is far and flow rate is very high then criteria is output 1mf16
17. If cost is inexpensive and Risk is low reliability and Distance is moderately close and flow rate is low then criteria is output 1mf17
18. If cost is inexpensive and Risk is low reliability and Distance is moderately close and flow rate is acceptable then criteria is output 1mf18
19. If cost is inexpensive and Risk is low reliability and Distance is moderately far and flow rate is high then criteria is output 1mf19
20. If cost is inexpensive and Risk is low reliability and Distance is moderately far and flow rate is very high then criteria is output 1mf20
21. If cost is inexpensive and Risk is low reliability and Distance is close and flow rate is low then criteria is output 1mf21
22. If cost is inexpensive and Risk is low reliability and Distance is close and flow rate is acceptable then criteria is output 1mf22

23. If cost is inexpensive and Risk is low reliability and Distance is close and flow rate is high then criteria is output 1mf23
24. If cost is inexpensive and Risk is low reliability and Distance is close and flow rate is very high then criteria is output 1mf24
25. If cost is inexpensive and Risk is low reliability and Distance is moderately far and flow rate is low then criteria is output 1mf25
26. If cost is inexpensive and Risk is low reliability and Distance is moderately far and flow rate is acceptable then criteria is output 1mf26
27. If cost is inexpensive and Risk is low reliability and Distance is moderately far and flow rate is high then criteria is output 1mf27
28. If cost is inexpensive and Risk is low reliability and Distance is moderately far and flow rate is very high then criteria is output 1mf28
29. If cost is inexpensive and Risk is low reliability and Distance is far and flow rate is low then criteria is output 1mf29
30. If cost is inexpensive and Risk is low reliability and Distance is far and flow rate is acceptable then criteria is output 1mf30
31. If cost is inexpensive and Risk is low reliability and Distance is far and flow rate is high then criteria is output 1mf31