The future of the Sub-Saharan African water supply system in small towns: A case study from Moamba

T.T. Nguyen

March 2021

The future of the Sub-Saharan African water supply system in small towns: A case study from Moamba

Author: Toan Nguyen

Student number: 4218930

Faculty of Civil Engineering, TU Delft, The Netherlands

Supervisors: Prof. Dr. Zoran Kapelan,

Dr. Ir. Doris van Halem,

Ir. Jasper Schakel,

Dr. Ir. Edo Abraham

Date: March 2021

Acknowledgments

This MSc. Thesis is a contribution to the AWC project with the focus on the small town in Mozambique. Although, the field visit to Moamba was cancelled, I still managed to create this MSc. thesis with the help of several important people. Therefore, I want to show my deep gratitude towards those important people in this section:

First, I would like to thank my chair of committee Dr.Ir. Zoran Kapelan who guided me patiently through the whole process. His advice and knowledge about the subject were always highly appreciated by me. Dr.Ir. Doris van Halem should be mentioned as well for providing me the opportunity to participate in this project, connecting me with the people in Moamba and her feedback was always on point. I would also like to thank my daily supervisor Ir. Jasper Schakel as well, for his support. Anytime I had a question about the MSc. thesis in general, he was always there to answer them. The advice of Dr.Ir. Edo Abraham is also appreciated. I would therefore like to thank him as well.

Furthermore, the local drinking water company provided me essential information about the water supply system and without their help I would have not been able to start my thesis. Mr. Keiven Gouveia and Mr. Tonecas Goetsa especially helped me a lot. Without their help I would not have been able to write this thesis.

Finally, I have to thank my family and friends who supported and motivated me during the covid-19 pandemic. It has been a long journey with ups and downs, but this thesis is for you all.

Yours sincerely,

Toan Nguyen

Abstract

This MSc thesis is a contribution to the African Water Corridor (AWC) project that gains insight into the future of water supply systems in the Sub-Saharan African small towns. The future water demand in these areas constitute a great challenge in the effort to provide safe water for everyone. Unfortunately, there are high uncertainties in the future posed by unforeseen changing factors such as global climate change and urbanization which makes it a challenge for decision-makers to develop strategies for these water supply systems in the long-term planning. The concept of resilience is introduced by many studies to address those uncertainties.

The objective of this thesis is to provide an approach for decision-makers to develop a resilience water supply system in small towns for long-term decision planning to answer the following research question:

'How can a water supply system in a small African town be resilient and provide sufficient water in the future?'

This thesis presents a methodology that is resilience-based and develops reduced future supply and increased future demand scenarios for the small town in a period of 30 years. To analyze the water supply systems in small towns, Moamba has been used as a case study. Scenarios with a low, moderate, and high impact on the water supply system were developed to overview the uncertain future with a time horizon of 30 years (2020-2050). Three potential supply-based intervention options (B1-B3) and five demand-based intervention options (A1-A5) were created to improve and evaluate the system performance of the water supply system in the future. In addition, resilience metrics were created and applied to evaluate this system.

The results of the case-study revealed that the individual interventions options improved the resilience of the water supply. However, the intervention with the best performance, Brackish desalination plant (B1), still had a maximum water deficit of three years. Moreover, it had a cost of 5.5 million USD. Since this might not be feasible for decision-makers, six strategies were created with different combinations of the individual intervention options (intervention strategies) to achieve the best possible resilient water supply system. These intervention strategies showed a better performance at resilience (with several strategies having a zero water deficit) which makes them in overall more feasible and acceptable for decision-makers.

As shown by this thesis, the presented resilience analysis approach provides a promising method to address future uncertainties and create reliable, long-term water resources planning. For future directions, further research into specific areas and more application of this resilience method on other small towns in Africa is needed to obtain more data about resilience in Sub-Saharan African small towns in general. Furthermore, other system performances such as vulnerability and reliability could be analyzed to optimize the resilience methodology for small towns.

Table of contents

List of Figures

List of tables

List of Abbreviations

AWC	African Water Corridor project
EPA	Environment Protection Agency (US Gov)
IWA	International Water Association
NGO	Non-governmental organization
RWH	Rainwater harvesting
SD6	UN Sustainable Development Goal 6
PVC	Polyvinyl chloride
UN	United Nations
USD	U.S. Dollar
WHO	World Health Organization

1. Introduction

1.1 Motivation

According to the United Nations, 'The access of safe drinking water and sanitation is recognized as a basic human right that is essential for the full enjoyment of life and all human rights. Yet, it is estimated that in 2018 844 million people did not have access to basic water services and that over 2.1 billion people still could not have access to safely managed drinking water WHO, (2017). In certain areas of Africa especially, the number of people who have access to basic water services is lower than 50 percent WHO, (2017). Unsafe drinking water services lead to exposure to water-borne diseases such as Cholera and Typhoid which can threaten many lives.

The United Nations,(2010) recognizes the threat of unsafe drinking water and has adopted the UN sustainable development goal (SD6) with the main goal *''Ensure availability and sustainable management of water and sanitation for all''*. The implementation of the SD6 goal depends on the requirements of each country. However, progress is stagnant for many countries. One of those countries is Mozambique. Water shortage and its poor quality are vital issues that threaten the health of the inhabitants of the country. In Mozambique, similar to other African countries, the maintenance of the existing water supply systems in small towns and the urban water supply systems differ significantly. Decision-makers are often neglecting those systems due to high costs and low revenue in this peri-urban area. This has an impact on nearly 15 percent of the Mozambican population that lives in those small towns. Still, the population in small towns has been growing over time due to its dynamic nature.

For example, intergovernmental development projects such as the Maputo Corridor in Mozambique will accelerate the economic growth further in small towns that are located along the trade routes of those development projects as mentioned by Bowland & Otto, (2012). On one hand, the small towns will therefore generate socio-economic opportunities for people in those areas, on the other hand, the water demand is rapidly increasing. Therefore, the small towns constitute the greatest challenge in the effort to provide safe water for everyone.

There are high uncertainties in the future posed by for example the global climate change, urbanization and other unforeseen changing factors which makes it a challenge for decision-makers to develop strategies for these water supply systems in the long-term planning.

The concept of resilience is introduced by many studies to address those uncertainties. Resilience is defined as the ability of a system to absorb and recover from a certain impact. In addition, resilient water supply systems are able to absorb and recover from the impact of the potential threats while maintaining a high level of drinking water service. Therefore, the development of resilient water supply systems for decision-makers in the future is necessary to create reliable, long-term water resources planning.

1.2 Objectives

As mentioned earlier, the development of resilience water supply systems is necessary for long-term water resources planning. Unfortunately, studies about the resilience of water supply systems in Mozambican small towns are limited. As an opportunity to fill in the gap, the aim of this thesis is to provide an approach for decision-makers to develop a resilient water supply system in small towns for long-term decision planning by using Moamba as a case study as part of the AWC project. This is formulated in the following research question:

'How can a water supply system in a Sub-Saharan African small town be resilient and provide sufficient water in the future?'

To answer this research question, a case study of Moamba has been used and several objectives were made in the progress as well:

- Develop reduced future supply and increased future demand (due to climate change and population growth) scenarios for the small town to project the future in a period of 30 years.
- Identify suitable demand-based and supply-based intervention options for small African towns to develop resilient water supply.
- Compare and evaluate the intervention options by using a multi-objective approach where cost and resilience performances are the main objectives.

2. Resilience theory and application in water supply systems

As mentioned in the introduction, in this thesis the resilience concept has been used to address the long-term water supply-water demand balance of the system. This system has a variety of aspects that deals with uncertainty. A resilient water supply system anticipates the impact of potential influences such as climate change and rapid urbanization. Resilience metrics and indicators are often used to evaluate the performance of the system by many articles. This will be described in more detail below.

2.1 Resilience theory

Metrics were introduced by several articles to evaluate the system performances of decision alternatives. According to Werner & Blythe (2014), a metric provides a relevant quantitative measure and is generally based on data (either derived or gathered through monitoring or surveys). Therefore, metrics are suitable to evaluate and monitor the performance of certain objectives in the decision-making processes. This concept allows decision-makers to have a structured overview of the performance of a system. Metrics are therefore applied for analysing the decision alternatives of the long-term water supply-water demand balance of the system in this thesis. Furthermore, an indicator is defined by Werner & Blythe (2014) to be a variable that compares the metrics to a certain threshold/ baseline. Indicators are essential in decision-making processes because decision-makers often base their decisions on the exceedance or non-exceedance of a certain threshold. In this thesis, the performance metrics are based on the concept of resilience.

Hashimoto et al. (1982) introduced resilience as one of the four system performance metrics in water resource planning. Resilience is defined here as the ability of a system to recover from a certain impact. Moreover, the resilience performance of a system depends on the ability to absorb, adapt, and recover from a certain impact. This concept combines the important indicators such as time and water deficit for water resource management planning. Hashimoto et al. (1982) used resilience by analyzing the time period that a system is transitioning from an unsatisfying state to the satisfying state. Several articles used his methodology as a reference to analyze the resilience of a system with several scenarios.

Evaluating a water supply system in the context of resilience has been applied by a few articles. Each article used a different method to analyze the resilience of the strategies of the water supply system.

As Pagano et al. (2019) described, available approaches for assessing water distribution network resilience can be broadly classified as 'property-based' or ' performance-based':

- 'Property-based' approaches investigate the susceptibility of water distribution networks to failure (Pagano et al., 2019). An example of a property-based approach is the Graph Theory. This approach links the resilience performance of the system with the properties of the water supply system such as capacity and connectivity (Yazdani et al., 2012). However, as stated by Pagano et al. (2019) and Yazdani et al. (2012), the increasing level of complexity and interconnection in water systems is a challenge for when using the Graph Theory since any change in the network characteristics has consequences on the hydraulic function.

- ‘Performance-based’ approaches require modelling of performance under multiple system failure scenarios, using hydraulic models (Pagano et al., 2019). An example of a performance-based approach is the Global Resilience Analysis. Diao et al. (2016) used the concept of resilience for the Global Resilience Analysis to evaluate the resilience with certain failure scenarios. This approach focuses on the failure modes regardless of the threat that may cause this failure (Pagano et al. 2019, Diao et al. 2016).

Unfortunately, there is scarce literature available about the comparison of the property-based approaches versus the performance-based approaches. However, according to Pagano et al. (2019), performance-based analyses might be crucial to better understand the response of water distribution networks to complex networks (such as pipe failure) where property-based approaches can provide insight to the behaviour and characteristics of global water distribution networks but might not be fully representative of hydraulic performances.

Therefore, in this thesis a performance-based approach has been applied to evaluate the water supply system in the context of resilience. Articles that have used the performance-based approach focus mainly on the level of service and the unsatisfying state of the system, as shown in Figure 1. This system is often exposed to a certain impact which results in a loss of service during a time period which is often defined as the unsatisfactory state. The ability to recover from the impact depends on the behavior of the system or elements of the system with or without the strategies or intervention options.

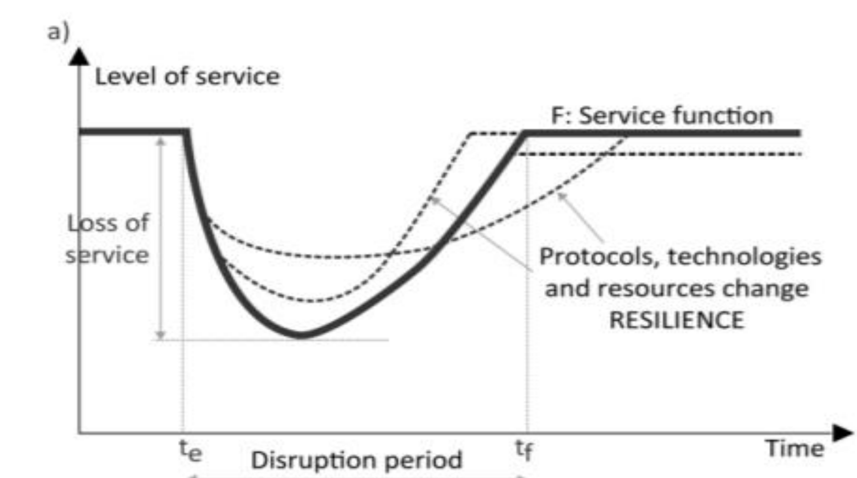

Figure 1: The concept of resilience (Cubillo et al, 2017).

2.2 Resilience metrics and indicators

The metrics and indicators to analyze the concept of resilience vary between the articles. Figure 2 shows several resilience metrics and indicators that have been applied. Different types of resilience metrics are described below.

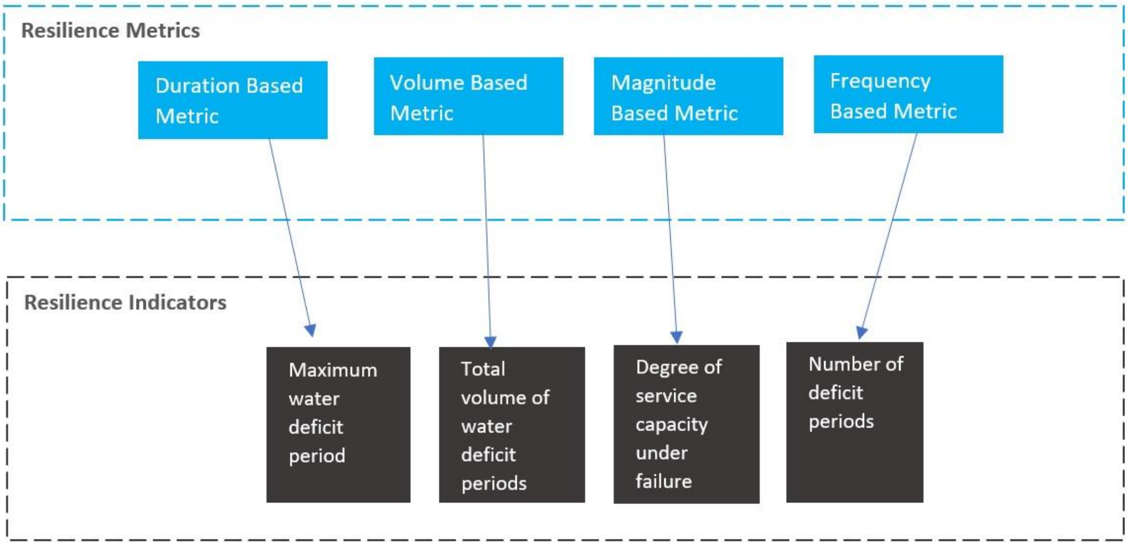

Figure 2: An example of metrics and indicators used in the resilience concept based on Roach et al. (2018)

2.2.1 *Time-based resilience metrics*

Time-based metrics are often used by several articles. According to EPA (2015), the time-base metrics provide detailed information about the advantages of resilience intervention options. Time-based metrics allow the decision-makers to calculate the effect of the resilience-based interventions on the system or the interactions by analyzing the disruption period of a failure event or the recovery period. For instance, Kjeldsen & Rosbjerg (2009), Cubillo et al. (2017) and Roach et al. (2018), used duration-based metrics to analyze the performance of resilience.

The maximum water deficit period is often implied as an indicator for the duration-based metrics. This indicator shows the maximum duration of water deficit in a certain time-horizon when the water demand exceeds the water supply. Roach et al. (2018) defined the water deficit as the time-period when temporary restriction on water supply should be implemented. In this metric, resilience (R) is defined as the maximum duration (d_j) in an unsatisfactory state of a water supply system. Kjeldsen & Rosjberg (2009) used the maximum value instead of the mean value of this indicator due to the influence of the small insignificant events which can lower the mean value.

As such, in this thesis resilience (R) is defined as follows (Roach et al. 2018, Kjeldsen & Rosjberg 2009):

$$R\ [t] = \{max(d_j)\}\ \ or\ R[t^{-1}] = \{max(d_j)\}^{-1} \qquad (1)$$

Where t is the time-period and d_j is the maximum duration in an unsatisfactory state of a water supply system.

2.2.2 Magnitude-based resilience metrics

Magnitude-based metrics focus on the magnitude of certain threats which can be tolerated by the water supply system according to Roach et al. (2018). Several articles such as Schoen et al. (2015) and Amarasinghe et al. (2017) used magnitude-based metrics to analyze resilience performance. However, the approach differs for each article. For instance, Schoen et al. (2015) used the magnitude-based resilience metrics to analyze the magnitude of the impact such as droughts or storms on certain critical system function. In this article, the loss of service is calculated for each failure event. Furthermore, the resilience performance is compared with the occurrence of failure.

Amarasinghe et al. (2017) used a different approach. They assessed the resilience of the water supply system by analyzing the capacity of maintaining the service level under several climate conditions and threats. Here resilience is defined as follows:

$$Rsp[-] = \frac{1 - Rss}{Rpp} \tag{2}$$

Where *Rsp* is the degree of service capacity, *Rpp* is the disruption and *Rss* is the level of service of the system under failure conditions in equation 2.

2.2.3 Volume-based resilience metrics

Volume-based resilience metrics show the total water volume of all the water deficit in a certain time horizon according to Roach et al. (2018). They proposed the volume-based metrics as one of the resilience metrics to analyze the system performance in water supply systems. The disadvantage of this metric is the uncertainty in its calculation. Roach et al. (2018) defined the total volume V_I as follows:

$$V_I = \sum_{i=0}^{i=I} m_i * d_i \tag{3}$$

Where V_I is the volume (*V)* of each water deficit event *i*, m_i is the magnitude of impact (m_i) and d_i is the duration of the water deficit event.

2.2.4 Frequency-based resilience metrics

Frequency-based resilience metrics are useful to show the occurrences of water deficit events in a certain time period. Roach et al. (2018) mentioned that the single frequency metrics cannot predict several performance aspects of resilience and therefore should be combined with other resilience metrics. Schoen et al. (2015) used the combination of magnitude and frequency-based metrics. The occurrence of failure events has been used and combined with the magnitude of the impact to analyze the resilience performance in water supply system in coastal areas.

2.3 Comparison of resilient strategies in water supply systems

In the context of resilience and long-term water resource planning, there have been different approaches and strategies developed and applied to aim for improvement of the water supply system. To compare these approaches and strategies, a distinction can be made between single objective approaches versus multiple objective approaches.

With the single objective approach, there is a focus on only one single requirement. Hall et al. (2019), for example, used the single objective method and focused solely on economic cost to compare the different strategies. The investment cost was the main criterium that compared the short-term intervention options and the long-term resilient intervention options to enhance the water supply system and show the most cost-effective strategy. Schoen et al. (2015) also used the single objective approach and focused solely on the resilience performance of several intervention options based on the reuse of water, wastewater and under several threats such as wildfires and storms. By using a quantitative analysis, the resilience of water supply system with those intervention options were compared to each other.

Unfortunately, the single objective approach might lead to bias decision when focusing on one requirement since decision-makers often have multiple requirements to improve the water supply system. Therefore, a multiple objective approach was suggested by Matrosov et al. (2015) that allows the decision-makers to analyse the trade-offs between the objectives.

Within the multiple objective approach, the resilience performance and the total cost are often used to compare each adaptive strategy with a certain threshold. In addition, Pareto optimal analysis have been carried out when a single objective is not able to describe the performance of a strategy (Costa et al. 2015). Pareto optimal analysis has been applied to show the decision-makers which optimal solutions are found between the trade-off of cost and resilience by using the pareto frontier. This line shows the optimal set of solutions between the trade-offs of several objectives. Todini (2000), for instance, applied this analysis to compare strategies to reduce the pipe failure with the cost. Roach et al. (2018) used the pareto optimal analysis to compare the strategies with system performances such as resilience, robustness, and total cost.

Multi-criteria decision-making analysis has also been used to compare the system performances of the alternatives in several scenarios on long term planning. This is also a multiple objective approach to analyse several objectives such as cost and resilience. This approach ranks the system performances such as resilience and robustness by using weighting criteria. For instance, Srdjevic et al. (2004) used this approach to compare the alternatives for complex water supply systems in long term planning.

3. Methodology

3.1 Development of supply/demand scenarios

The future of the water supply system in a small town such as Moamba is uncertain as said in previous sections. When future conditions happen to be different from the predicted conditions, strategies that were developed based on these conditions may fail to deliver their expected performance (Hall al. 2012).

To address this, the concept of multiple plausible futures has been used in this thesis. The concept deals with several conditions that do not fit in one single future. In addition, the multiple plausible futures concepts explore the changes of certain processes that go beyond the future knowledge in this system. It is an approach that has received growing attention from researchers and decision makers (Fazey et al., 2016) and is a convenient approach to address the future of water supply systems with data scarcity.

The multiple plausible futures concepts require scenarios. Explorative scenarios were used in this thesis because these scenarios explore the unknown future impact or occurrence of certain influences or drivers. Moreover, due to their explorative nature, decision-makers will gain insight into the potential issues in the future before implementing intervention options.

The explorative scenarios in this thesis are based on the characteristics of a small town with certain conditions which is illustrated in Figure 3. To show a variety of potential futures, scenarios were used with influences that differed in the impact on the water demand and supply (high/ moderate/ low) of the system in small towns. Furthermore, the main scenarios are based on common influences or drivers for the water supply system in small towns: climate change or population growth.

The complexity of the drivers in the water supply systems is addressed by creating sub-scenarios. Proposedly, the three main scenarios represent the possibilities of urbanization while the sub-scenarios show the difference in future climate conditions (dry and wet).

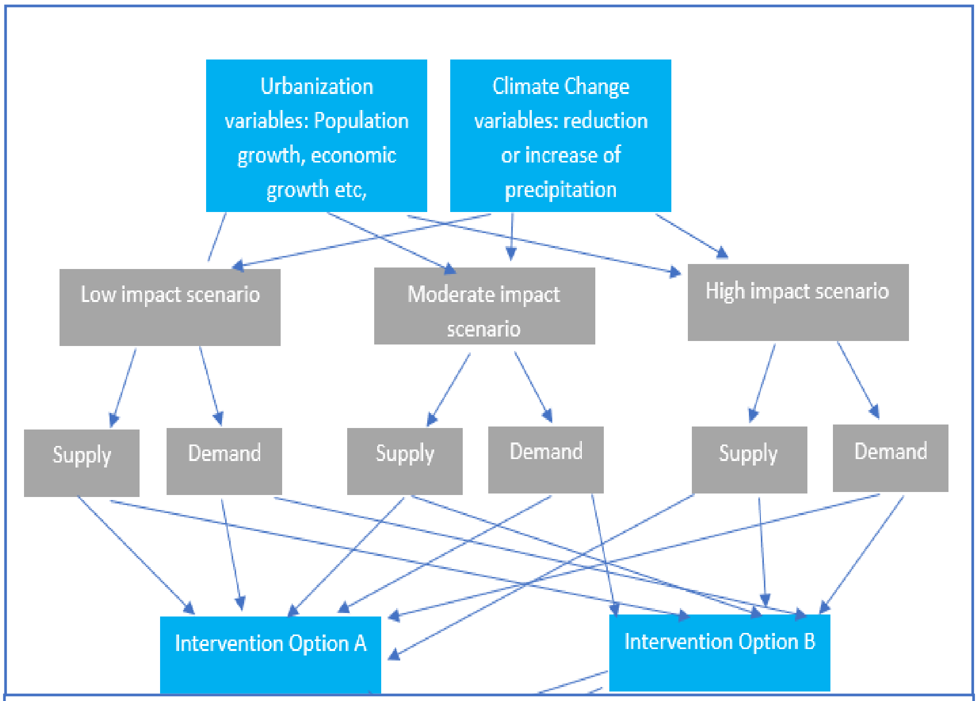

Figure 3: Illustration of the creation of explorative scenarios.

After defining the main drivers, the variables were defined as well. The variables of each driver have a high, moderate, or low impact on either the water demand or water supply in the future. For instance, population growth is a variable of the driver of urbanization that has an impact on water demand, while the change of precipitation might change the water supply of the water supply in small towns.

3.2 Intervention options

After the development of the supply/demand scenarios, the intervention options were identified. Suitable options were based on the characteristics of the water supply system in small towns (high leakage/ illegal tapping/ dynamic changes in the system/ low maintenance) as defined by IWA (2015) and shown in Table 1. Intervention options that address the leakage, improving the flexibility of the system, and conserve water were mainly considered for improving the water supply system in small towns. Furthermore, the options were categorized into water demand and water supply based intervention options (Table 1):

- For instance, water-saving methods and technologies, pressure management technology, and replacement of pipes were proposed to address the leakage and illegal water tapping in a small town. Those options will reduce high water losses in the water supply system in small towns.
- Greywater reuse and rainwater harvesting systems are mainly applied as water conservation solutions. In this thesis, rainwater harvesting is applied to support the water supply while greywater reuse reduces the water demand in the system.
- Desalination plants are often proposed as an alternative water source that is potentially used in areas with brackish groundwater or in coastal areas.
- Community-based intervention options are also proposed to address the water supply system. Small intervention options such as public awareness campaigns are also therefore implemented options.
-

Table 1: Characteristics of the water supply system in small towns.

	Water demand intervention options					**Water supply intervention options**		
Characteristics of the water supply system in small towns	Water saving methods	Pressure management technologies	Decentralized Greywater reuse	Replacement of pipes	Public awareness campaigns and education	Commercial household tanks	Desalination plant	Rainwater harvesting systems
High Leakage	Direct Impact	Direct Impact	No Impact	Direct Impact	Direct Impact	No Impact	No Impact	No Impact
Illegal Tapping	Direct Impact	Direct Impact	Indirect Impact	No Impact	Direct Impact	No Impact	No Impact	Indirect Impact
Dynamic changes in the system	No Impact	No Impact	Direct Impact	Direct Impact	Indirect Impact	Direct Impact	Direct Impact	Indirect Impact
Low maintenance	Indirect Impact	Indirect Impact	No Impact	Direct Impact	Direct Impact	Direct Impact	No Impact	Indirect Impact

3.3 Resilience Assessment

The system performance of the water supply system in small towns is evaluated in the resilience metrics. To compare the intervention options, the resilience and the total cost are used as the main variables, as also shown in Figure 4.

3.3.1 Duration metric: Water deficit period

It is proposed by Roach et al. (2018) to use the duration metrics with the water deficit period as an indicator to quantify the resilience. Roach et al. (2018) stated that the maximum duration metric is the most suitable resilience duration metric for estimating the system performance due to the comprehensible and precise characteristics. This metric shows the time recovery of a system due to a system failure or a certain impact. The maximum number of years with system failure is assumed as the water deficit period. The implementation of intervention options (demand and supply) will show the impact on the water deficit periods. As a projection, the maximum duration of water deficit will reduce. Furthermore, it is assumed that the water shortage on the supply side is caused by those water deficit periods. In this thesis, the annual water deficit periods in the future are compared with the baseline period in 2020 as a threshold.

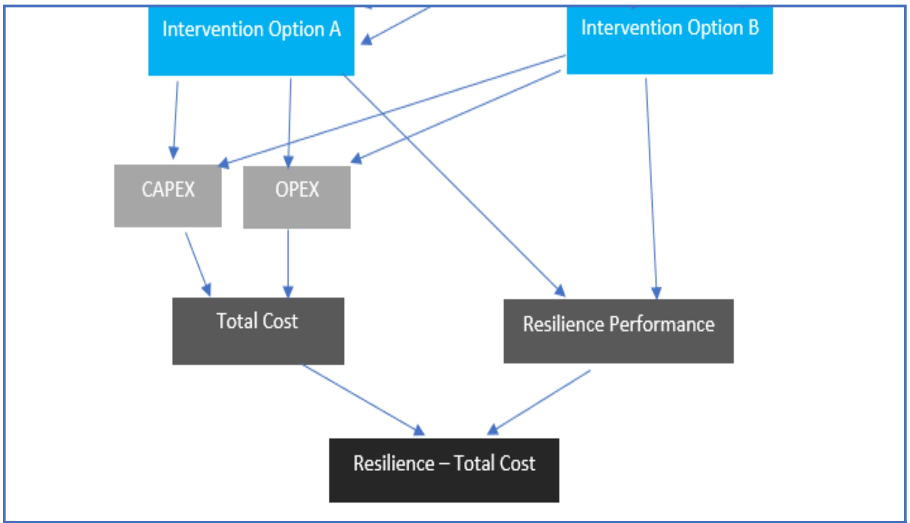

Figure 4: Resilience metrics.

Generally, the water deficit periods are defined in months or in days. Martinez-Codina & Cubillo (2017) preferred to use days since this provides more accurate data. However, since this thesis is focusing on long-term water supply/demand, the water deficit period is expressed in years.

The maximum annual water deficit period is defined as follows by Roach et al. (2018):

$$R\ [years] = \{max(d_j)\} \tag{4}$$

Where R is resilience (the smaller the value in years the higher the resilience), d_j is the duration of the deficit time period (years).

3.3.2 Robustness

Different resilience performances might occur between the scenarios for an intervention option or strategy. Therefore, the robustness is introduced to compare the resilience performance of each intervention option and strategies between the different scenarios. Robustness is commonly described in water resources literature as the degree to which a water supply system can maintain performance at a satisfactory level across a broad range of plausible future scenarios or conditions (Matrosov et al. 2013, Roach et al. 2018).

In this thesis, the robustness of the strategy is defined in equation (5) (Roach et al. 2018):

$$Rob\,[\%] = A/U \tag{5}$$

Where *A* is the number of scenario combinations (of supply and demand) under which the system maintains a given level of resilience and *U* is the total number of scenario combinations considered.

3.3.3 Total Cost

As shown in Figure 4, besides the resilience, the total cost is also used to compare the intervention options with each other.

The total cost is defined as follows (Roach et al. 2018):

$$PV\ [USD] = \frac{CAPEX}{(1+r)} + \frac{OPEX}{(1+r)^{y+1}} \tag{6}$$

Where the total cost is expressed in terms of Present Value (*PV*) and r as the interest rate. The CAPEX, OPEX, and interest rate (r) are used as parameters for the total cost in the following equation. The present value illustrates the impact of cost over the years when the intervention option is applied. The implementation year is (Y).

3.4. Model for assessing supply/demand balance over the planning horizon

The model to assess the future supply-demand balance is divided into several steps. The variables are defined for each high, moderate, or low impact scenarios. The input variables are then separated into demand-based variables and supply-based variables. It is therefore inherent that the variables have an impact on the water demand and water supply of each scenario. Furthermore, the water demand and water supply will change each year until the end of the planning horizon. The connections of the model are shown Appendix C.

The intervention options are also input variables for the model with the changing cost and impact on the water demand or water supply of each scenario. It is proposed that intervention options A1-A6 have an impact on the water demand. The impact of water demand of each year for each intervention option is defined as follows:

$$Water\ demand_{ij}[m^3/year]\ =\ waterdemand_j\ -\ reduction\ option_i \tag{7}$$

Where *j* is the scenario and *i* is the intervention option.

The impact of the supply-based intervention options is also calculated for each year and each scenario which is defined as follows:

$$Water\ supply_{ij}\ [m^3/year]\ = Water\ supply_j +\ increase\ option_i \tag{8}$$

Where *j* is the scenario and *i* is the intervention option.

To analyze the maximum water deficit period, the water shortage of each year has been calculated with the equation:

$$Watershortage_{ij}[m^3/year]\ = Waterdemand_{ij} - Watersupply_{ij} \tag{9}$$

Where *j* is the scenario and *i* is the intervention option.

The resilience performance is calculated by analyzing the water shortage of the water supply system of each scenario. The maximum water deficit period is counted for each scenario and each intervention option. The comparison of intervention options and strategies has been done by a multi-objective approach which uses the average resilience performance and the total cost as the objectives. This will show the decision-makers potential intervention options to create a future resilient water supply system in small towns.

4. Case study

4.1 Case study overview: Current state of Moamba water supply/ demand

4.1.1 Moamba water supply system

It is important to recognize the current water supply/demand balance of Moamba and the water issues in this system before analyzing the future. More detailed information about Moamba can be found in Appendix A of this thesis. The water supply system of Moamba is divided into two main categories: the intake and water treatment facility and the distribution network (Figure 5).

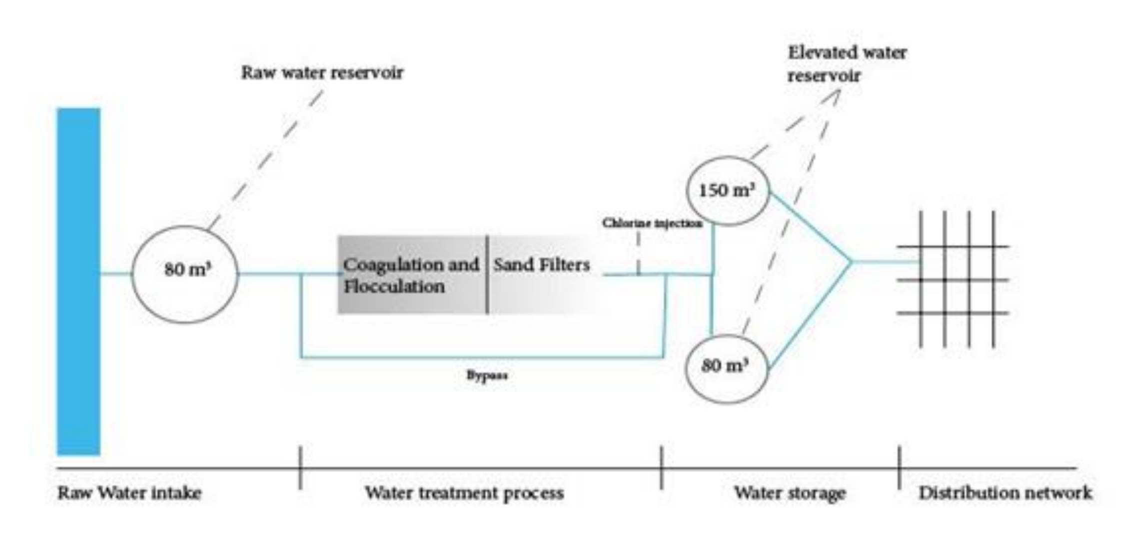

Figure 5: Water infrastructure of Moamba.

The river Incomati is the main water resource for the inhabitants of Moamba. The system for supplying drinking water has four processes: raw water intake, water treatment process, storage, and distribution of this treated water according to Silva-Novoa Sanchez et al. (2019).

The water flows from the intake point of the Incomati river into the raw water reservoir according to Silva-Novoa Sanchez et al. (2019). Subsequently, this raw water will be treated in water treatment facilities. There is also a bypass that has been used by operators to redirect the water to the elevated reservoir. In this bypass, the operators inject chlorine to treat the water. Furthermore, the treated water is pumped to two elevated reservoirs which have a capacity of 150 m^3 and 80 m^3. Afterward, this treated water is distributed to Moamba by gravity.

As shown in Figure 5, the two elevated reservoirs or water towers provide water to the distribution network of Moamba. The water operators supply once per day water from 10:00 until 17:00 (seven hours) to the six neighbourhoods of Moamba. This includes Bairro Central, Cimento, Madiquine, Livine, Bairro 25th June, and Sul. The pipes in the distribution network consist of highly dense Polyethylene (PVC) with a common size range of 75 - 200 mm. Furthermore, the pipes are shallowly buried in the soil to avoid theft by the local people.

4.1.2 *The water demand/supply balance of Moamba*

The current water shortage of Moamba has been calculated by using the current water supply and water demand of Moamba's water supply system. The annual distributed water is $5.5*10^5$ m^3 in 2019 according to Collins (2020). The billed water consumption is $3.3*10^5$ m^3 in this small town. It should be mentioned that several connections are inactive or unbilled in the water supply system which depicts an inaccurate water demand of Moamba.

The residential water consumption is defined as follows (Collins 2019):

$$Water\ demand_i\ [m^3/year] = pop[-]\ * dwc\ [l/p/d]\ +\ iwc\ [m^3/year] + pwc\ [m^3/year]\ +\ waterloss[m^3/year] \tag{10}$$

Where *i* is the year, *pop* is the population, *dwc* is the the daily water consumption per capita, *iwc* is the industrial water consumption and *pw* is the public water consumption. Collins (2020) defined the *dwc* as 46 l/p/d.

As mentioned before, the water demand is, unfortunately, higher in comparison with the water supply. As a result, the system has an annual water shortage in 2019 of $5.0*10^4$ m^3. On average, each person has a lack of 5.5 L per day in Moamba. In the future, this number will probably rise due to certain influences as discussed in the introduction.

4.1.3 *The challenges of the Moamba water supply system*

The challenges of the water supply system in Sub-Saharan African small towns are similar for this case study. Silva-Novoa Sanchez et al. (2019) mentioned that the water supply system in Moamba is characterized as an intermittent water supply system. This is caused by several factors which are discussed further in this section.

Water loss

A prominent issue of this small town is the high-water loss in the distribution network. This is caused by several factors. For instance, the water supply system is often exposed to ruptures and leakages in the distribution network in Moamba. This is partly caused by the fragile pipes of the distribution network and low maintenance due to funding. In 2019, 35 days with interruptions due to pipe bursts were noticed by the local drinking water company (Collins 2019). All those mentioned factors contribute to the current physical water loss of 32% in this system.

Population growth

Population growth has also an important impact on the water supply system in Moamba. In 2019, the inhabitants without access to the water supply system was $6.7*10^3$ which is projected to increase in the future due to the influx of migrants (Collins 2019). Silva-Novoa Sanchez et al. (2019) mentioned that new migrants often extend the infrastructure due to the rapid increase of settlements. However, the installation of those pipes is often unauthorized by the local drinking water company that results in pipe failure as well.

Climate and water supply

Moamba experiences the occurrence of drought events which has a major impact on the water supply system. De Boer & Droogers (2016) mentioned that between 2020 and 2100, 10% of the precipitation will be reduced in the regional area. The drought affects the river flow that results in a low water table in the Incomati River. Consequently, the water supply system has often implications to abstract the raw water from this river. This has an impact on the water supply and puts pressure therefore to provide sufficient water for the inhabitants of Moamba. One of the main causes for this drought is climate change. Therefore, climate change will worsen the water availability significantly.

4.2 Scenarios of uncertain future developments affecting water supply and demand

To address future uncertainties such as climate change and rapid urbanization, three main scenarios (S1, S2 and S3) were developed to represent a small number of plausible but different future pathways, in the time-horizon from 2020 to 2050 (Figure 6). These scenarios were based on potential changes of the small town with scenario S2 representing a set of plausible future conditions with the highest impact on the small-town water supply system, while scenario S3 represents a set of plausible future conditions with the lowest impacts on the small-town water supply system. In addition, scenario S1 represents a set of plausible future conditions with moderate impact on the small-town water supply system.

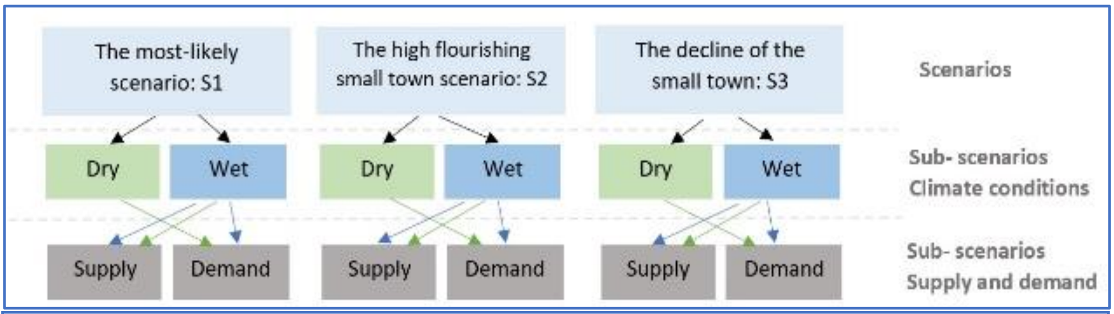

Figure 6: The three main developed scenarios for the case-study.

Furthermore, the main scenarios were divided into water demand and water supply sub-scenarios, as shown in Figure 6 and Table 2. All these scenarios differ from each other due to the influences of different variables, as shown in Table 2. The water supply sub-scenarios were affected by the variables 'change of precipitation 'and 'upstream abstractions. The water demand sub-scenarios were mainly influenced by the variables 'economic growth', 'population growth' and the 'change of water loss' in the future. In Appendix B, the calculation of these variables for this thesis is described in further detail.

The main scenarios S1, S2 and S3 along with their sub-scenarios are described in detail in Table 3 and in the following sections.

Table 2: Sub-scenarios and the different variables.

Sub -scenarios	Variables
Water Supply	Change of precipitation [%]
	Impact of upstream water abstraction
Water Demand	Population growth
	Change of unit consumption [%]
	Change of industry activity [%]
	Change of public and services activity [%]
	Change of water loss [%]

Variables	Scenarios							
	Most likely scenario – dry scenario (S1a)	Most likely scenario – wet scenario (S1b)	The flourishing small town with upstream influences dry (S2a)	The flourishing small town without upstream influences wet (S2b)	The flourishing small town with upstream influences scenario wet (S2c)	The flourishing small town without upstream influences dry (S2d)	The decline of the small-town dry scenario (S3a)	The decline of the small-town wet scenario (S3b)
Population growth [%]	Moderate annually population growth (2.1) %	Moderate annually population growth (2.1) %	High annually population growth rate (3.1%)	High annually population growth rate (3.1 %)	High annually population growth rate (3.1 %)	High annually population growth rate (3.1 %)	Low annually population growth (-0.2 %)	Low annually population growth (-0.2 %)
Economic Activity [%]	Moderate annual increase of water demand due to the increase of economic growth of 4 % for industry and 11% for public and commercial sectors	Moderate annual increase of water demand due to the increase of economic growth of 4 % for industry and 11% for public and commercial sectors	High annual increase of water demand due to the economic growth 6% for industry and 8 % for commercial and public sector	High annual increase of water demand due to the economic growth 6% for industry and 8 % for commercial and public sector	High annual increase of water demand due to the economic growth 6% for industry and 8 % for commercial and public sector	High annual increase of water demand due to the economic growth 6% for industry and 8 % for commercial and public sector	No economic activity for industry (0 %)	No annual economic activity for industry (0 %)
Change of unit consumption. Baseline (50 L/p/d) (Demand)	No change of daily water consumption per capita (0%) on the water demand	No change of daily water consumption per capita (0%) on the water demand	Annual daily water consumption per capita increase of 3.37 % on the water demand	Annual daily water consumption per capita increase of 3.37 % on the water demand	Annual daily water consumption per capita increase of 3.37 % on the water demand	Annual daily water consumption per capita increase of 3.37 % on the water demand	No change of daily water consumption per capita (0%) on the water demand	No change of daily water consumption per capita (0%) on the water demand
Change of water loss. (Baseline 32%) (Demand)	No change in water loss on the water demand	No change in water loss on the water demand	2.29 % annually decrease of water loss on the water demand	2.29 % annually decrease of water loss on the water demand	2.29 % annually decrease of water loss on the water demand	2.29 % annually decrease of water loss on the water demand	0.83 % annually increase of water loss on the water demand	0.83 % annually increase of water loss on the water demand
Upstream abstraction [%] (Supply)	No upstream abstraction	No upstream abstraction	Annually abstraction of upstream areas (1.25 %) on the water supply	No upstream abstraction	Annually abstraction of upstream areas (1.25 %) on the water supply	No upstream abstraction	No upstream abstraction	No upstream abstraction
Change of water availability [%] between 2020-2050 (Supply)	The reduction of precipitation of 3.8 % on the water supply	The increase of precipitation of 3.8 % on the water supply	The reduction of precipitation of 10 % on the water supply	The increase of precipitation of 10 % on the water supply	The increase of precipitation of 10 % on the water supply	The reduction of precipitation of 10 % on the water supply	The reduction of precipitation of 3.8 % on the water supply	The increase of precipitation of 3.8 % on the water supply

Table 3: The list of scenarios and variables as considered for this case study.

4.2.1. The most likely scenario (S1)

This scenario represents a set of plausible future conditions with moderate impact on the small-town water supply system. Scenario S1 illustrates what will happen in the future with the water supply and demand if the current trend continues over 30 years and the variables will not change over time.

The variables that affect the water demand such as the economic and population growth in the S1 scenarios are relying on the current trend of the development of Moamba. The current population growth of 2.5% Deloitte (2016) and the daily water consumption per capita of 46 L/p/d from Collins (2019) have been used to project the future residential water consumption in this scenario. Furthermore, the number of commercial companies in Moamba is currently slightly growing over the years. According to Macario et al. (2016), 49 commercial companies were connected to the water supply system in 2015 while the connections have been increased to 59 for the commercial sector in this small town in 2019. This is an annual increase of nearly 3%. Therefore, the public and commercial water consumption is assumed to grow annually with 3% for both the S1a and S1b scenarios. Besides that, the industrial growth is assumed to rise with 4% for all S1 scenarios, which is based on the industrial growth projection of OECD (2017) for Mozambique. Thus, since scenario S1 assumes a continuation of the current trend, it is assumed for all S1 scenarios that the water demand will increase annually due to the described increased water consumption and population, commercial, public, and industrial growth.

The impact of the water supply variables is different for the sub-scenarios. This is elaborated below.

- S1a represents the dry scenario. In this sub-scenario, the decrease of precipitation has an impact on the water supply of Moamba. According to De Boer & Droogers (2016), the precipitation is projected to reduce with 10% between 2020 and 2100 in the Mozambique region. This is used in this thesis as a reference for the reduction of the water supply in Moamba. It is assumed that the water supply will reduce with 3.8% in 2050. This number is calculated by linearizing the projected reduction of 10% in 2100 based on De Boer & Droogers (2016).
- The other sub-scenario, S1b, illustrates the opposite of S1a as the wet scenario. In this case, the annual precipitation will slightly increase over time with an assumed 10% increase of precipitation in 2100 as the counterpart of S1a. By linearizing this value, the water supply will increase with 3.8% between 2020-2050.

4.2.2. The flourishing small-town scenario (S2)

This scenario represents a set of plausible future conditions with the highest impact on the small-town water supply system. Moamba has the potential to grow rapidly as a small town due to economic developments in the region, for example the Maputo Corridor project. In this scenario, Moamba flourishes with high economic activities and therefore attracts people from the other regions to settle in this small town. As a result, variables such as population growth, daily water consumption per capita and industrial growth will have a larger impact on the water demand of the small town than scenario S1 and are likely to increase significantly. As an example, it is assumed that the population growth will increase annually with 3.1%. This growth is similar to the upper predicted 95% high interval provided by the United Nations (2019) as a future projection of the population growth of Mozambique.

Due to the assumed population growth, there is a likelihood that Moamba will transition from a small town to an urban area. This will have an impact on the variable water consumption and therefore the water demand. In Mozambique, urban areas such as Maputo have a higher daily water consumption per capita than the small towns. In this thesis, therefore, the unit consumption has been increased linearly for all S2 scenarios from 46 L/p/d to 100 L/p/d in 2050. The 100 L/p/d is derived from the unit consumption of Maputo (Farolfi et al., 2014). On average, the annual unit consumption will change with 3.37% for all S2 scenarios which is based on the increase from 46 to 100 L/p/d between 2020 and 2050. Furthermore, it is assumed that the public, commercial, and industrial growth will rapidly increase with an annual growth of 6% which is in the range of the future projection of the economic growth of Mozambique (OECD, 2017).

The water supply variables for the S2 scenario are different from the S1 scenario. As shown in Table 3, the upstream abstraction variable is also considered in the S2 scenario. As a result, scenario S2 is divided into four sub-scenarios:

- As the regional economic development might lead to an increase of water demand in the upstream areas nearby Moamba, the influence of the variable upstream abstraction is considered in the sub-scenarios S2a and S2c. Deriving from the reduction of the average Incomati discharge between South Africa and Mozambique (De Boer & Droogers, 2016), it is assumed that the water availability will reduce annually with 1.25% in these scenarios;
- The sub-scenarios S2a and S2d are dry scenarios. This means that in both S2a and S2d, the impact of the reduction of precipitation on the water availability (and therefore the water supply) is assumed to be significantly higher than the other sub-scenarios. In this thesis, based on De Boer & Droogers (2016) it is assumed that in these sub-scenarios the precipitation between 2020 and 2050 will have a reduction of 10%. This means that the water supply is substantially decreased in both S2a and S2d, while the water demand is substantially increased as mentioned above;
- S2b and S2c are wet sub-scenarios. S2b sub-scenario has similar properties as the sub-scenario S2c. However, unlike sub-scenario S2c, the water supply of the small town in sub-scenario S2b is not affected by the upstream abstractions. In contrary to the S2 dry sub-scenarios, it is assumed for both sub-scenarios S2b and S2c that there will be an increase of water availability (and therefore a substantial increase of the water supply) of 10% between 2020 and 2050 (De Boer & Droogers, 2016).

4.2.3. The decline of the small town (S3)

This scenario represents a set of plausible future conditions with the lowest impacts on the small-town water supply system. Scenario S3 is what will happen with the small town if the inhabitants of Moamba are moving to major urban areas such as Maputo. In this scenario, the small town has a low attractiveness which is caused by the stagnant economic development. As a result, the population growth is decreasing over time with an estimation of 0.2%. This number is based on the lowest population growth in Mozambique between 1980 and 2020 (World Bank 2020). The unit consumption remains the same as the current trend with 46 L/p/d (Collins, 2019) with no changes over time. Furthermore, the development of industries, commercial companies and public sectors are stagnant over the years. This means that the public, commercial, and industrial sector have zero annual growth.

The water loss is considered to increase over time in this scenario due to assumed lack of maintenance. According to Macario et al. (2016), the water loss in 2015 was 49 percent in Moamba. It is assumed that the water loss will increase over time between 30 and 49 percent. Therefore, it is assumed in thesis linearly from 32 percent in 2020 to 40 percent in 2050 with an average annual percentage increase of 0.83%.

Thus, in comparison to the S1 and S2 scenarios, it is assumed for all S3 scenarios that there will be a significant less impact on the water due demand due to the described reduction of the population growth and stagnation of the economy.

As shown in Table 3, scenario S3 is divided into 2 sub-scenarios:

- Sub-scenario S3a is a dry sub-scenario, where the influence of the reduction of precipitation is assumed to be the same as sub-scenario S1a. This means a similar reduction of 10% in 2100 in this region and so a reduction of 3.8% between 2020 and 2050.
- Sub-scenario S3b is a wet sub-scenario, where the influence of the increase of precipitation is assumed to be the same as sub-scenario S1b. This means a similar growth of 10% in 2100 in this region and so an annual growth of 3.8 percent.

4.2.4 Future projections of supply and demand

Most likely scenarios (S1)

As shown in Figure 7, the most likely scenario (S1) shows that the water supply system will not provide sufficient drinking water for the inhabitant of Moamba in the future. The water demand increases rapidly while the water supply reduces slightly over time. Water demand increases mainly due to the contribution of the population growth in the S1 scenarios. The current trend depicts the increased water demand over time with 1.2 million m^3 water. The gap between water demand and water supply will therefore grows over time.

The scenario shows the importance of the implementation of several intervention options to create a resilient water supply system.

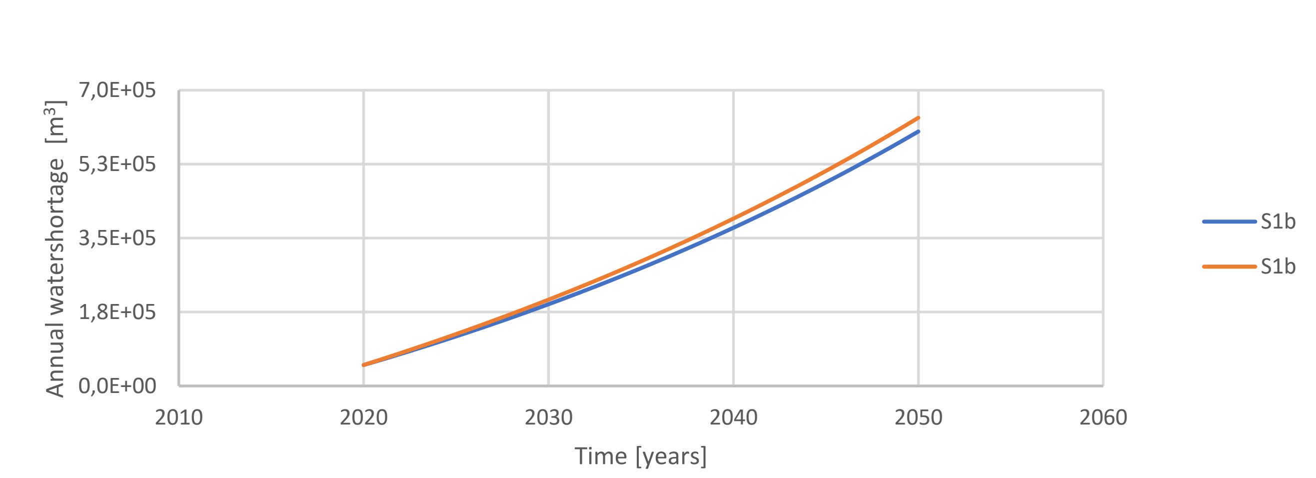

Figure 7: Most likely scenarios S1 between 2020-2050.

High flourishing small town scenarios (S2)

As shown in Figure 8, the high flourishing small town scenarios (S2) depict different water demand and water supply scenarios in comparison with the most likely scenarios (S1). As expected, the S2 scenarios present a larger water demand over the time horizon of 30 years. The impact of the growing population and the increase of economic activities contributes to the high water demand in this small town. This explains the rapid rise of the S2 water shortage curves in comparison with the S1 scenarios right after the start of time horizon.

As an observation, the S2a scenario has the largest water demand out of the four sub-scenarios and the largest reduction of water supply due to the upstream abstractions and the impact of drought. The water shortage is therefore almost two times larger than the S1 water shortage.

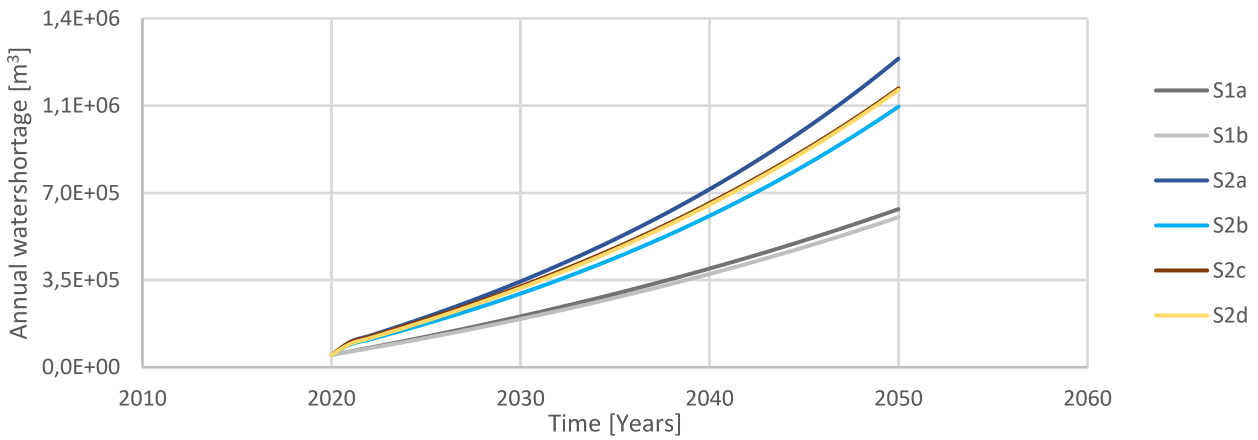

Figure 8: The most likely scenarios curves (S1s) in comparison with the flourishing small-town curves (S2s) between 2020-2050.

Decline of the small-town scenarios (S3)

The decline of the small-town scenarios, as shown in Figure 9, show a decline of the population in Moamba which results in lower residential water consumption. Furthermore, the development of industries, commercial companies and public institutions remains the same as in 2019.

Moreover, it is noticed that the water demand of S3a and S3b are slightly increased over time. This is mainly caused by the increase of the water loss variable from 30 percent to 40 percent water loss in 2050. The water demand of S3 is much lower than the water demand of S1. The water supply of S3 wet and dry scenarios are the same as the S1 wet and dry scenarios. In addition, the gap between water demand and water supply still occurs in this scenario, although the gap or water shortage is smaller than in the most likely scenarios. Therefore, small intervention options will likely close the gap in S3 scenarios.

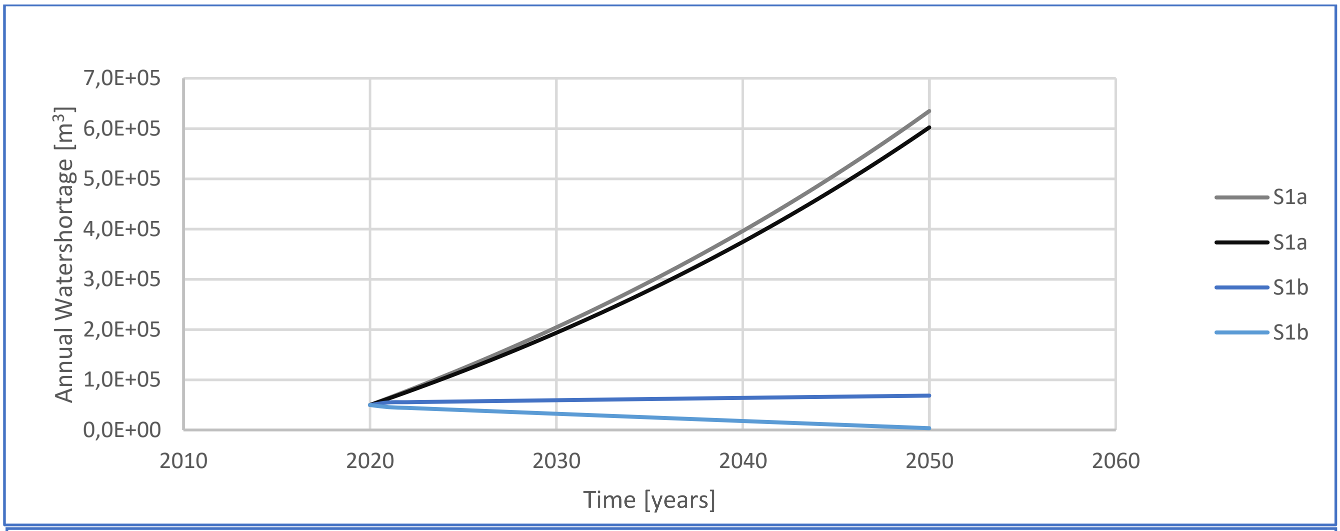

Figure 9: The most likely scenarios curves (S1s) in comparison with the declining scenarios curves (S3s) between 2020-2050.

4.3 Intervention Options

The possible intervention measures that can be used to address the supply/demand deficit are shown in Table 3. In this table, the potential reduction of water demand, supply or water loss are based on the literature for each intervention option. Those intervention options are elaborated in this section.

Table 4: The list of strategic interventions as considered for this case study.

List of intervention options	Code	Intervention Impact on annual supply or demand in [m^3/year]	CAPEX [$]	OPEX [$/year]	Lifespan
Implementation of rooftop rainwater harvesting tanks in households and schools (Supply) (Batchelor, 2011)	A1	Reduction of $2.7*10^5$ m^3/year on water demand	$2.5*10^6$	$1.3*10^5$	25 years
Grey water reuse for toilet flushing in public schools and offices (Demand) (Godfrey et al., 2009)and ("Gerador de Precos Mozambique," 2020)	A2	Reduction of $1.5*10^4$ m^3/year on water demand	$3.3*10^4$	$9.0*10^3$	25 years
Installation of pressure management technology in the small town with the pipe maintenance Time, flow and bulk control devices and pressure reducing valves (Demand) (IWA, 2015)and (al., 2017)	A3	Reduction of $1.8*10^5$ m^3/year on water demand	$2.9*10^4$	$3.1*10^4$	10 years
Application of smart water meters (Demand) ("Smart Pressure Management," 2020), and (IWA, 2015)	A4	Reduction of $8.8*10^3$ m^3/year on water demand	$2.5*10^5$	$7.7*10^3$	10 years
Public Awareness (Demand) (Katz et al, 2016)	A5	Reduction of $3.0*10^3$ m^3/year on water demand	1735	-	
Desalination plant with RO or ED with photovoltaic modules (Supply) (IWA, 2015)	B1	Increase supply of $1.1*10^6$ m^3/year	$6.0*10^6$	3985	10 years
The water supply of Moamba major dam (Supply) (Assumed Local Drinking water company)	B2	Increase supply of $1.1*10^5$ m^3/year	$4.1*10^6$	$2.0*10^4$	50 years
Implementation of household tanks (Demand)	B3	Increase supply $2.4*10^5$ m^3/year	$1.8*10^6$	$2.2*10^5$	25 years

A1 Rainwater harvesting

Rainwater harvesting (RWH) has been applied over the past centuries with a wide range of water use. This alternative resource provides water for water-consuming sectors such as agriculture and the domestic sector according to Kahinda & Taigbenu (2011). Rainwater is a safe drinking water source if the rainwater is collected correctly and the tank is well maintained. Rainwater harvesting tanks are therefore an adaptation measure that can cope with climate change and be used against water scarcity due to not only its ability to alleviate the pressure on the water supply by substituting tap water for potable or non-potable purposes but also its ability to reinforce the water cycle management by for instance reducing the external water demand of the small town (Jing et al., 2017) and thus, the water demand of the water consumers.

In this case-study, the annual precipitation is assumed to be 571 mm per year (Republica de Mocambique Ministerio da administracao estatal, 2005). The difference between the rainfall inflow and the water demand of the inhabitants of Moamba have been used to dimension the storage capacity of rainwater harvesting tanks. The water demand is calculated with the daily water consumption per capita of 46 l/p/d. The calculated annual inflow is 147241 m^3 in 2020 which has been used as the reference for dimensioning the tanks. However, the precipitation presumably fluctuates in the rainfall season and dry season ranges between 0 - 170 mm (Republica de Mocambique Ministerio da administracao estatal, 2005). The maximum capacity of the tanks without spillage is therefore 3 m^3. The tanks are often sized as 2.5 m^3 or 5 m^3. In this thesis, a 5 m^3 storage tank is assumed to avoid spillage. Furthermore, the tanks are implemented in schools, households, and offices. Presumably, new settlements will be provided with the rainwater tanks each year. The reduction of the required demand in the network is therefore $2.7*10^5$ m^3 which increases over time. In overall, this intervention option will reduce the annual required water demand with 25 percent, with a life expectancy of 25 years and a cost per unit of 361 USD. The total cost to implement this intervention option is therefore $2.5*10^6$ USD.

A2 Greywater reuse

Carden et al. (2010) analysed the reuse of disposable greywater in non- sewer areas. Several potential benefits are linked with this option. Greywater is defined as effluent water obtained from sewage flows of for example households and commercial buildings, but it excludes wastewater discharge from toilets, kitchen sinks, and dishwashers. As such, greywater is normally lightly polluted with no faecal component (Khor et al., 2020). However, water treatment is still necessary before reuse to avoid any health risks.

When treated, greywater can be applied in the agricultural, public, and domestic sectors for non-potable activities such as flushing toilets, watering gardens or lawns, and landscaping (Khor et al., 2020) It is reported that about 25–30 percent of potable water consumption can be reduced by reuse of greywater Vuppaladadiyam et al., (2018). Therefore, greywater reuse is a sustainable water management strategy that can lower the water demand significantly.

For this case-study, the intervention option of greywater reuse is based on the studies from Godfrey et al. (2009) and Aluslaili et al. (2015) about greywater reuse in schools. The greywater production for seven schools is assumed to be 7.5 L/p/d. Furthermore, a water consumption reduction of 21 percent for offices is assumed as well. The number of students and the water consumption of the offices have been used to calculate the total water saving. The cost per unit is 831 USD with a life expectancy of 25 years. The total of grey water reuse is therefore assumed to $6.3*10^4$ USD with a reduction of $1.5*10^4$ m^3/year. It should be mentioned that since these numbers are derived from greywater reuse in solely schools and offices and not for example domestic purposes, this intervention option has a small contribution to the water supply.

A3 Pressure management

Pressure management is an effective option that includes time, flow, bulk control, and pressure reducing valves in the system. This adaptive measure helps to reduce the real water losses by monitoring the pressure of the water distribution network. IWA (2015) mentioned that pressure management reduces residential water consumption by 40 percent in Khayelitsha by active maintenance of the pipes. This has been used as a reference for this case-study of Moamba. The lifespan of the system is considered ten years which is similar to the pressure management devices of Smart Pressure Management (2020). However, it is assumed that the pressure management technology will need to be replaced every ten years. Therefore, the cost is assumed to be $2.9*10^4$ USD with the OPEX of $3.1*10^4$ USD considering the replacement of pipes maintenance.

A4 Smart water metering

Smart water meters are also potential method to reduce the amount of non-revenue water. This technology provides and stores precise data of the household water consumption in a short time interval. The detection of leakage and real-time water consumption provides knowledge for the consumers and the drinking water company.

The water-saving capacity of smart meter feedback on households has been studied by Moglia et al. (2018). In this study, the reduction of water consumption due to the use of the smart water meters ranges between 3 – 20 percent. For this case-study, it has been assumed that the smart water meters have a 20 percent decreasing impact on the residential water consumption every year. Furthermore, the smart water meters are assumed to be installed in 3099 junctions nearby the households to gain knowledge about the leakages and illegal tapping. The cost is considered as $2.5*10^5$ USD with the OPEX of $7.7*10^3$ USD. The smart water meters are replaced every ten years.

A5 Public awareness campaigns

The impact of these tools on the water supply/demand system is discussed by several articles such as Moglia et al. (2018) and Quesnel & Ajami (2017). Quesnel & Ajami (2017) modelled the impact of the public attention through news media on the residential water consumption in the San Francisco Bay area and concluded that the impact of public awareness reduced 11-18 percent of the residential water consumption in California. This could be site specific, therefore, Moglia et al. (2018) stated that public awareness campaigns can reduce the water consumption between 2 -20 percent.

For this case-study, it is assumed that the impact of the campaigns reduces 5 percent of the residential water consumption with an impact of $2.0*10^4$ m^3/year. The cost for implementation is considered for 30 years 1841 USD.

B1 Desalination plant

The solar brackish desalination plant is an alternative water supply source that converts brackish water into potable water by using reverse osmosis (RO) or electrodialysis (ED) modules. It is a sustainable option that uses photovoltaic modules to provide energy for this water treatment facility in arid areas with low maintenance. This option has been implemented in arid and semi-arid areas with water scarcity to increase the water supply. Although water production is low, it has the potential to grow as an alternative water resource in the future. The potential capacity depends on the brackish groundwater. Several articles have mentioned the production capacity of the brackish desalination plants with RO or ED. IWA (2015) found a production capacity between 10 - 3000 m^3 per day. Therefore, for this case-study, it is proposed to use a RO brackish plant with $3.0*10^3$ m^3/day in the future. The unit construction cost depends on the capacity and treatment of the system. IWA (2015) stated that solar brackish desalination plants have an average unit cost in the range of 4 - 7 USD per m^3. Therefore, the assumption for this case-study is that the unit cost for the brackish desalination plant is 5.5 USD per m^3.

The CAPEX of the proposed solar desalination plant has a cost of 6.0 million USD. Al et al. (2010) considered a RO desalination plant with an investment cost between 0.5- 4.2 million USD. The OPEX considers only the maintenance and removal of RO modules. The cost of the membranes is retrieved by JICA (2014). In total, the OPEX is 3985 USD/ year.

The life-expectancy of brackish desalination plants is 30 years.

B2 Extra water supply from the dam

According to the local drinking water company, the water supply from Corumana Dam or Moamba Major Dam is considered to provide water for the inhabitants of Moamba in the future without the current access to drinking water. The cost for providing the water supply from the dam is currently discussed by the local authorities. Therefore, assumptions of the CAPEX and OPEX have been made. As a reference, the Maputo Greater Area project has been used to estimate the cost (CAPEX).

The World Bank (2020) shows the investment cost of 178 million USD to install the main transmission drinking water pipelines from the Corumana Dam to Matola and develop new household connections in the Maputo greater area. It has been estimated to provide $5.6*10^5$ people with drinking water in this area with an average increase of $1.3*10^5$ m^3/year on the water supply. The total cost per capita is therefore 317 USD per person to improve the system.

Therefore, it is assumed that the CAPEX is 4.1 million USD to construct for the current 6877 inhabitants without access to the water supply in Moamba (Collins et al., 2010). In the future, more connections are created with regards to the water supply from the dam. The cost for this is implemented in the OPEX with the assumption of $2.0 *10^4$ USD/year. This value is based on the study of JICA (2014) in Mozambique where they used 0.5% from the CAPEX to calculate the OPEX for constructing the dams.

B3 Household tanks

In Maputo, the capital of Mozambique, the water supply system is not able to provide sufficient potable water. Therefore, several households are using household tanks as an alternative source of water supply. According to Silva-Novoa Sanchez et al. (2019), the inhabitants of Moamba also often store water due to the ruptures and interruption of the water supply system. It is therefore proposed to implement for each household a tank of 5 m^3 with a monthly refill of the tank. The CAPEX is $1.8*10^6$ USD which is based on the cost of the household tank in Mozambique. The household tanks are each implemented for new settlements. This included in the OPEX of $2.3*10^5$ USD. This intervention option will support and thereby increase the water supply with an average of $2.4*10^5$ m^3/year. The life expectancy is considered 50 years.

5. Results

5.1 Resilience performance of the intervention options

The results show some interesting aspects of each intervention option. It should be noted that for this case-study it has been assumed that the individual intervention options were applied at the same time during the time-horizon of 2020-2050 and this does not differ between the interventions. It is proposed to implement the intervention options at the start of the time horizon due the occurrence of the water deficit in 2020. Furthermore, the resilience of the individual intervention or strategy is depicted as the average annual water deficit period across the multiple scenarios because the worst and best annual water deficit of scenarios do not show the whole picture of the resilience performance over the scenarios.

As shown in Table 5, the resilience performance varies between intervention options and scenarios. When comparing the intervention options solely, the resilience performance of B1 (Desalination plant) has the best performance with a maximum water deficit of 3 years and the resilience performance of A2 (Greywater reuse) and A5 (public awareness campaigns) have the worst performance with a maximum water deficit of 30 years. In overall intervention option B1 performed well in all scenarios. This can be explained due to the fact that the brackish desalination plant uses the brackish groundwater as supply source. The production capacity of this option is therefore not limited by the changing climate conditions and other influences such as upstream abstractions. Furthermore, this intervention option provides a large reduction of the water demand over the years with a production capacity of $3.0*10^3$ m^3/d. This will therefore result in a high resilience performance. Therefore, as can be seen in Table 5, intervention option B1 has five scenarios without annual water deficit.

Table 5: The list of intervention options within green the best resilient performance and red the worst for each scenario and each intervention option

	Resilience performance (Annual water deficit in years)							
	S1a	S1b	S2a	S2b	S2c	S2d	S3a	S3b
Intervention option A1	26	23	27	25	27	26	0	0
Intervention option A2	30	30	30	30	30	30	30	30
Intervention option A3	21	20	25	22	24	24	0	0
Intervention option A4	28	29	30	29	30	30	0	0
Intervention option A5	30	30	30	30	30	30	30	30
Intervention option B1	0	0	3	0	1	1	0	0
Intervention option B2	26	25	28	27	28	28	0	0
Intervention option B3	18	17	22	20	21	21	0	0

As mentioned before, the intervention option A5 (Public awareness campaigns) and A2 (Greywater reuse) performed poorly in terms of resilience. This could be explained by the fact that A5 only reduces 5% of the residential water consumption over time as mentioned in the previous chapter and thus has little effect on the water supply/demand system compared to for instance intervention option B1 (Desalination plant). The greywater reuse system performs also poorly in the scenarios because the greywater reuse is focusing on the public water consumption. Unfortunately, the public water consumption is low in comparison with the residential water consumption. Therefore, the greywater reuse in schools and offices only addresses a limited amount of the actual water demand which results in a low resilience performance in all scenarios.

The resilience performance also varies significantly between the scenarios of each intervention. This is caused by the different impact of the variables on the scenarios. In overall, the intervention options performed low on the S2 scenarios (high flourishing small town) in comparison with the other scenarios. This is as expected since the S2 scenarios represented future conditions with the highest impact on the small-town water supply system (high increase of water demand due to economic and population growth while the water supply is decreasing) and so the resilience, which again is the ability to recover from an impact, is expected to be low. More specifically, it is shown that the intervention options show the lowest resilience performances in the dry sub-scenario S2a which indicates that the combination of the variables water availability (which is decreased in the dry sub-scenarios) and upstream abstraction (which is the only difference between sub-scenario S2a and sub-scenario S2d) has a significant impact on the resilience performance.

In contrast, the S3 scenarios represented future conditions with the lowest impact on the small-town water supply system (lowest water demand and highest water supply out of all 3 scenarios) and so it is expected that the resilience is the highest for these scenarios. As shown in Table 4, for most of the intervention options in the S3 scenarios, the maximum resilience has been achieved with a water deficit of zero. Unfortunately, this is not the case for intervention option A2 (greywater reuse) and A5 (smart water meters) in these scenarios. This means that even in the scenarios where impact on the water demand/supply system is relatively low, these intervention options still have a very high resilience and therefore it is indicated that these intervention options might not be suitable. It should be noted that intervention option A2 was specific for schools and offices. If the implementation of this option would be more broadly (for example for households and agriculture), its resilience performance might improve.

Robustness of the individual options

The robustness of the intervention options is compared in Figure 10. In this case, intervention option B1 (desalination plant) is still the best option with 62% robustness for all scenarios which is to be expected since this intervention option achieved the maximum resilience performance in the S1 and S3 scenarios as described above. Unfortunately, intervention option B1 could not achieve a high resilience performance in the S2 scenarios which explains why it did not achieve the maximum percentage (100%) of robustness.

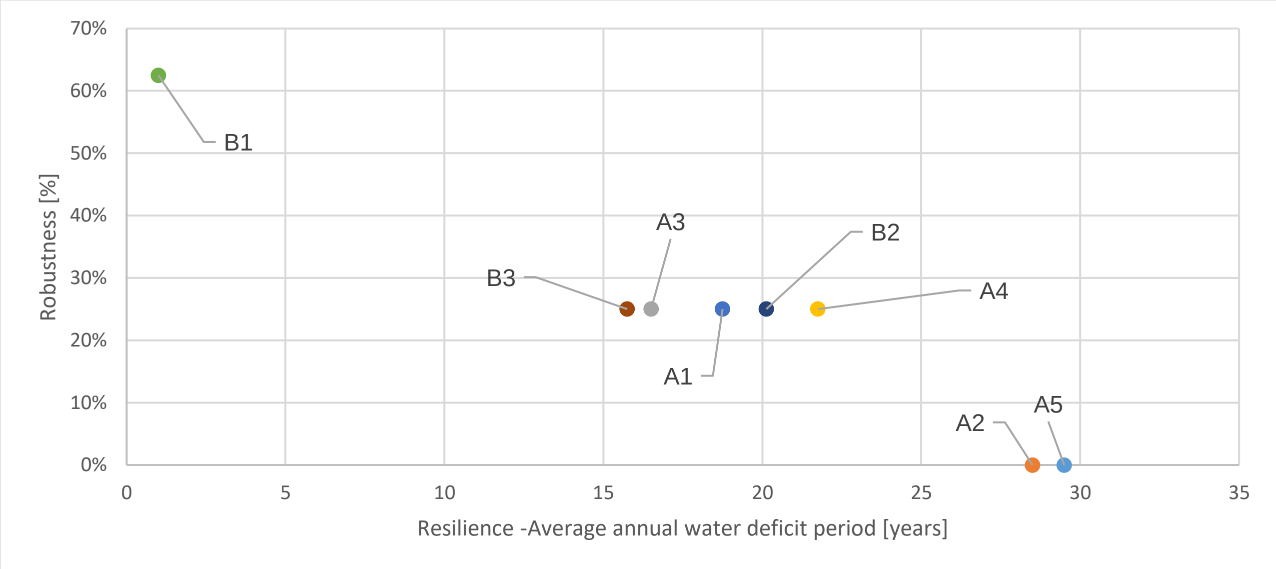

Figure 10: Robustness and resilience of individual intervention options.

Noticeably, five intervention options have a robustness of 25%: B3 (Household tanks), A3 (Pressure management technology), A1 (Rainwater harvesting tanks, B2 (Extra water supply from the dam) and A4 (Smart water meters). This is caused by the fact that they all achieved zero maximum water deficit in S3 scenarios as shown in Table 5 due to the small gap between water demand and water supply over the years which is also mentioned in the previous section.

Intervention options A2 (Greywater reuse) and A5 (Public awareness campaigns) showed the lowest robustness (0%) which is explained by their poor resilience performance and low impacts on the scenarios, as described before.

5.2 Total Cost – Resilience performance of the individual intervention options

The intervention options as listed in Table 5 were compared by analyzing the average resilience (in years) and the total cost (in USD) between 2020 and 2050. The average resilience was calculated by averaging the different scenarios S1, S2 and S3. As mentioned earlier, intervention B1 (desalination plant) has the best resilience performance with the best robustness in this case-study. However, as shown in Figure 11, the total cost for B1 is also the highest in comparison to the other intervention options with 5.5 million USD due to the high construction cost to implement the system. Therefore, decision-makers might tend to choose a more cost-effective solution. For instance, intervention option A3 (Pressure management technology) has a significantly lower total cost than B1 (88425 USD) and has a better performance in resilience (16.5) than the A1-A4 interventions. This intervention option addresses the demand well by reducing the water consumption in the system and the water loss. The cost is therefore lower than B1. However, an important note on the results in Figure 11 is that, in terms of resilience, the goal is to have zero water deficit, which not one of the intervention options in Figure 11 achieves. Therefore, none of these options are good in terms of resilience and the likelihood of these options to be selected is very low.

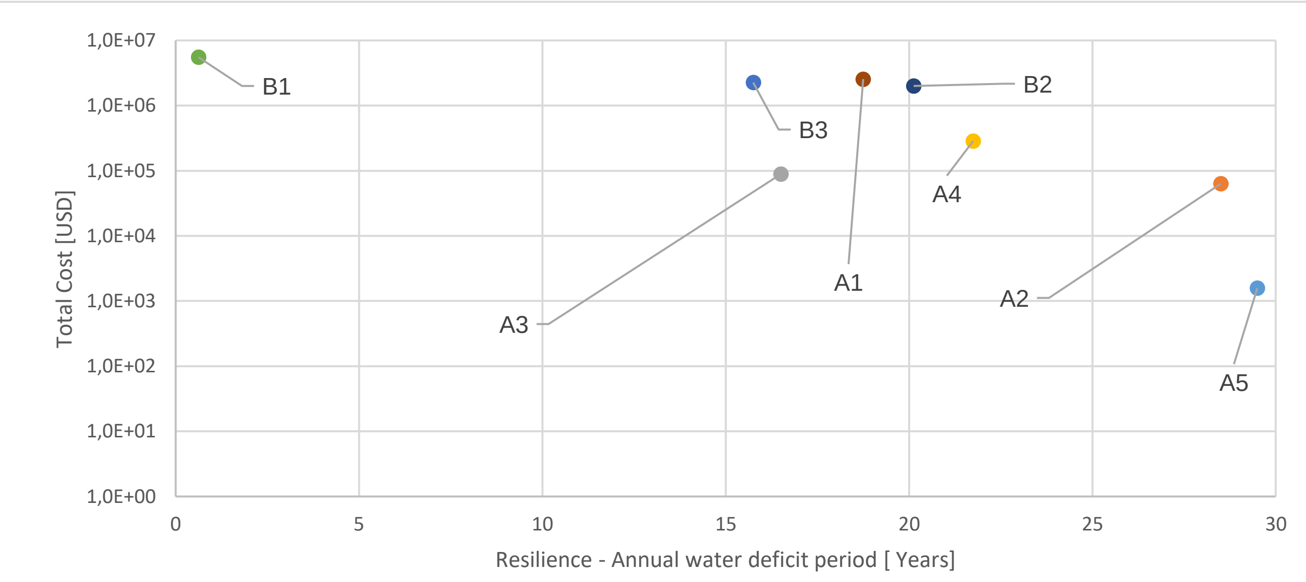

Figure 11: Impact Intervention options on Moamba's water supply between 2020 -2050

5.3 Intervention Strategies

As shown in the previous section, individual intervention options can improve the resilience of the water supply but only up to a certain point. However, as stated earlier the annual water deficit still occurs in each intervention option between 2020 -2050 for several scenarios and due to the costs, some strategies might not be achievable. Therefore, six strategies were created with different combinations of the individual intervention options (intervention strategies) to achieve the best possible resilient water supply system. The main characteristics of the six strategies are described in Table 6. These six strategies were manually selected and based on the possible options implied by the local drinking water company to improve the system. Their calculation is shown in Appendix D.

Table 6: Main characteristics of the intervention strategies.

Intervention strategies	Stand-alone interventions							
	A1	A2	A3	A4	A5	B1	B2	B3
AS1			X	X	X		X	
AS2	X	X						X
AS3	X					X		
AS4			X	X		X		
AS5	X		X	X				
AS6			X	X	X			

Each intervention strategy shows a different implementation of intervention options, as shown in Table 6. Furthermore, the implementation time of each intervention option depends on every scenario. To simplify the implementation period of the strategies in scenarios, the time-period of implementing the strategies is based on the high impact scenario (S2).

Certain patterns are similar as shown in Table 7 when the interventions are implemented. Unfortunately, since this is already a current problem, the annual water deficit period is set to start in 2020 as mentioned in the previous sections. All of the intervention strategies are therefore already starting in the time period of 2020-2025. However, as shown in Table 7, the different individual interventions within these strategies are implemented separately throughout the time-horizon of 2020-2050. Furthermore, the time-period for when these interventions are implemented differ during the chosen time-horizon. For example, Pressure management technology (A3) are preferred to implement first to address the current water loss in the fragile system. This will address the gap between water demand and water supply in the near future. Smart water meters (A4), rainwater harvesting tanks (A1) and household tanks (B1) are following after the pressure management technology. The brackish water supply plant (B1) and the extra water supply of the dam (B2) is proposed to implement in the period of 2025 and 2030 due to consideration of the construction period.

Table 7: Implementation of intervention strategies AS1-AS6 during time-horizon of 2020-2050.

intervention strategies	2020-2025	2025-2030	2030-2035	2035-2040	2040-2050
AS1	A3	A4	B2		
AS2	A1, B3			A2	
AS3	A1	B1			
AS4	A3, A4	B1			
AS5	A3, A1	A4			
AS6	A3, A4, A5				

5.3.1 AS1 – The interconnected water supply system strategy

AS1 is proposed as the strategy with the focus on improving the accessibility to the Moamba water supply system and the current water supply system to reduce water loss in the system. As shown in Table 8, this strategy combines the pressure management technology with smart water meters and awareness campaigns to reduce the water loss and indirectly the residential water consumption in the system. The current water supply system is connected with the mains of the dam by providing water to the people without access to the Moamba water supply system.

The resilience performance of this strategy performs well in the wet scenarios with a robustness of 50 percent. As shown in Table 8, five scenarios (S1a, S1b, S2b, S3a and S3b) have zero water deficit period. Scenario S2a has the worst resilience performance with a maximum water deficit of 8 years.

The total cost is 4.6 million USD for the implementation of this AS1 in all scenarios.

Table 8: Intervention strategy AS1 with the resilience performances for each scenario.

	Resilience performance (Maximum water deficit years)							
	S1a	**S1b**	**S2a**	**S2b**	**S2c**	**S2d**	**S3a**	**S3b**
Intervention strategy AS1	0	0	6	0	3	3	0	0
Average resilience performance	1.5							

5.3.2 AS2 - The communal blue grey strategy

This strategy is based on handing the control over to the inhabitants of Moamba. AS2 strategy will therefore put less pressure on the local drinking water company to intervene. This strategy means that the current water supply system will not be improved to reduce water loss but rather focus on water conservation with storage and reuse intervention options. This is proposed as a hybrid system with the implementation of commercial household tanks with rainwater to support water supply. The tanks are implemented for all residential houses in the small town. Each year, new settlements are provided with this tank to maintain the accessibility to provide sufficient drinking water. Furthermore, greywater reuse systems are implemented to reduce water consumption in schools and offices. This option therefore relies less on the river Incomati as the main water source.

The resilience performance of this strategy performs less than AS1 strategy with only three scenarios (S1b, S3a and S3b) without water deficit period due to the low impact of greywater reuse (Table 9). Scenario S2a has the worst resilience performance with a maximum water deficit of 16 years.

The total cost to implement this strategy is 4.7 million between 2020 and 2050.

Table 9: Intervention strategy AS2 with the resilience performances for each scenario.

	Resilience performance (Maximum water deficit years)							
	S1a	**S1b**	**S2a**	**S2b**	**S2c**	**S2d**	**S3a**	**S3b**
Intervention strategy AS2	10	0	13	4	11	8	0	0
Average resilience performance	5.875							

5.3.3 AS3 - The support of alternative water sources strategy

Strategy AS3 focuses on alternative water sources to support the water supply system in Moamba. This strategy differs from AS1 due to its solely focus on the storage and reuse of drinking water. AS3 has only two intervention options: rainwater harvesting tanks (A1) and the brackish desalination plant (B1). It is proposed to provide every household with rainwater harvesting tanks between 2020 and 2050. The purpose is to improve the accessibility of the system while the brackish desalination plant will support the water supply in Moamba to provide sufficient drinking water in the system.

As shown in Table 10, the AS3 performs well for every scenario with zero water deficit between 2020 and 2050. However, it should be mentioned that the cost of this strategy is unfortunately high with 8.8 million USD.

Table 10: Intervention strategy AS3 with the resilience performances for each scenario.

	Resilience performance (Maximum water deficit years)							
	S1a	**S1b**	**S2a**	**S2b**	**S2c**	**S2d**	**S3a**	**S3b**
Intervention strategy AS3	0	0	0	0	0	0	0	0
Average resilience performance	0							

5.3.4 AS4 – The Support of alternative water source with water loss reduction methods

This strategy has similar intervention options to strategies AS1 and AS3. However, in AS4 brackish desalination is implemented to support the current water supply while pressure management technology and smart meters address the water loss in the small town. This strategy proposes a lower capacity of brackish desalination plant with $2.0*10^3$ m^3/d to provide water instead of the $3.0*10^3$ m^3/d. As a result, this strategy shows a lower cost with 4.9 million USD than for AS3.

As shown in Table 11, strategy AS4 performs well in overall. Only scenario S2a has an annual water deficit of one year. The other scenarios show no deficit period in this case.

Table 11: Intervention strategy AS4 with the resilience performances for each scenario.

	Resilience performance (Maximum water deficit years)							
	S1a	**S1b**	**S2a**	**S2b**	**S2c**	**S2d**	**S3a**	**S3b**
Intervention strategy AS4	0	0	1	0	0	0	0	0
Average resilience performance	0.125							

5.3.5 AS5 - The blue grey solution with water loss reduction

The AS5 strategy focuses on the rainwater harvesting tanks with grey water reuse system for the water supply system, similar to the AS2 strategy. However, in this strategy, the current water supply system is also maintained and improved to address the water loss by using pressure management technology and smart water meters. The accessibility is here addressed by placing rainwater tanks in each household. As shown in Table 12, the resilience performance of this strategy has six scenarios (S1a, S1b, S2b, S2d, S3a and S3b) without water deficit. However, scenario S2a shows a water deficit period of 7 years which brings the average resilience performance of this strategy to 1.4 in years. The robustness in this case is here 75 percent with a cost of 4.7 million USD.

Table 12: Intervention strategy AS5 with the resilience performances for each scenario.

	Resilience performance (Maximum water deficit years)							
	S1a	**S1b**	**S2a**	**S2b**	**S2c**	**S2d**	**S3a**	**S3b**
Intervention strategy AS5	0	0	3	0	1	0	0	0
Average resilience performance	0.5							

5.3.6 AS6 – The improved water supply system strategy

AS6 strategy focuses on the connected water infrastructure in the Maputo development. This strategy uses the current water supply system to provide water in Moamba with water source Incomati. It is similar to the AS1 and AS3 strategy but differs in that AS6 only focuses on the water loss reduction methods with public awareness, without the external supply from the dam. As shown in Table 13, all the S1 and S2 scenarios show high water deficits in years. The robustness is therefore only 25 percent with only the S3 scenarios without the water deficit. However, the cost to implement this is 3.5 million USD which is low in comparison with the other strategies.

Table 13: Intervention strategy AS6 with the resilience performances for each scenario.

	Resilience performance (Maximum water deficit years)							
	S1a	**S1b**	**S2a**	**S2b**	**S2c**	**S2d**	**S3a**	**S3b**
Intervention strategy AS6	9	7	19	14	18	17	0	0
Average resilience performance	10.5							

5.4 Robustness – Resilience performance overview for the Intervention strategies

The robustness- resilience performance of the intervention strategies is shown in Figure 12. AS3 strategy (the alternative water source strategy) is the best strategy in terms of both robustness 100% and resilience (zero water deficit in all scenarios). This indicates that the combination intervention B1 (Brackish desalination plant) and A1 (rainwater harvesting tanks) works well in terms of addressing the water demand and water supply. Furthermore, the intervention options are complementary to each other. For example, when interruptions occur in the brackish desalination plant or the current water supply system, the inhabitants can still rely on the rainwater harvesting systems to provide sufficient drinking water.

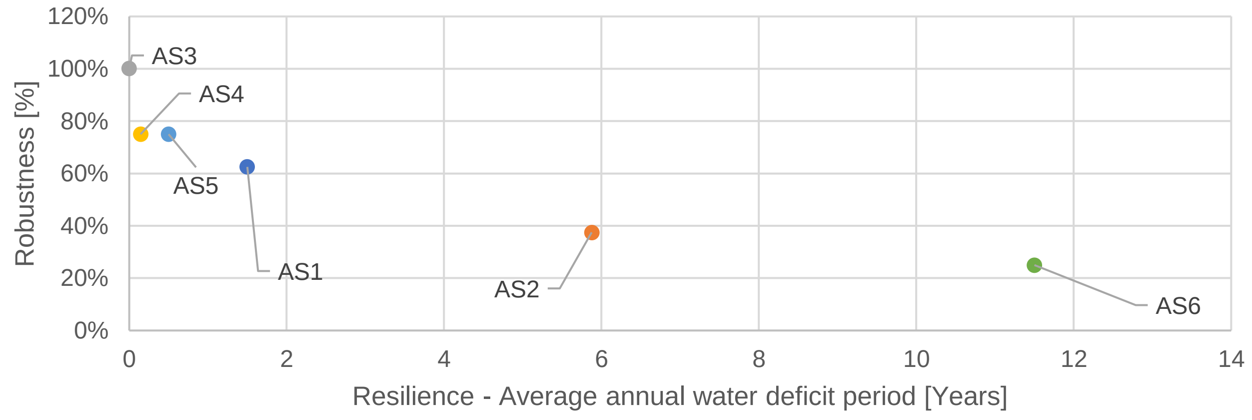

Figure 12: Robustness and resilience of Intervention strategies.

As shown in Figure 12, strategies AS4 (the Support of alternative water source with water loss reduction methods strategy) and AS5 (the blue grey solution with water loss reduction strategy) both have a similar robustness of 75%. This is explained by the fact that both strategies have five scenarios without annual water deficit. However, even though they have the same robustness percentage, AS4 and AS5 differ in their resilience performance, as can be seen in Figure 12. The AS4 strategy performs better in terms of resilience in comparison with the AS5 strategy. This is mainly caused by the fact that the B1 intervention (brackish desalination plant) in AS4 strategy with a production capacity of $2.0*10^3$ m^3/d has a bigger impact on the water supply than the B3 intervention (household tanks) in AS5 strategy.

Strategy AS6 (improved water supply system) shows the lowest average resilience performance of 11.5 and lowest robustness 25%. This can be explained by the fact that the combination of intervention options A4 (smart water metering) and A5 (pressure management methods) only addresses the water demand and in particular the water losses without any additional water supply. Therefore, it makes sense that strategy AS6 shows the lowest average resilience performance (11.5) in years and is the least favourable strategy.

5.5 Total Cost – Resilience overview for the intervention strategies

The maximum resilience performance and total cost of the strategies are considered in Figure 13. As mentioned before, strategy AS3 shows the best resilience option with zero water deficit period. However, the total cost for this strategy ($9.0*10^6$ USD) is also the highest in comparison to the other strategies which might not be feasible for decision-makers. Such a high cost is caused by the high construction and labour cost for both rainwater harvesting tanks and brackish desalination plant in comparison with the water loss reduction methods.

Figure 13 shows that AS4 has an average resilience performance close to zero and a significantly lower cost than AS3. AS4 strategy consists of the B1 intervention (brackish desalination plant) with a lower production capacity than in AS3 and water loss reduction interventions (A3 and A4) that generally already have a low cost. The brackish desalination plant has a lower CAPEX of 4.0 million USD instead of 6.0 million USD compared to B1 in AS3 strategy. This strategy with the total cost of 4.9 million USD is therefore a promising strategy when the budget is prioritized by the local drinking water company.

Strategy AS6 has the lowest total cost compared to the other strategies due to implementation of only water loss reduction methods such as pressure management methods(A3) and smart water metering (A4). Those intervention options have a low cost in comparison with the expansive intervention options such as rainwater harvesting tanks (A1) or brackish desalination plant. For instance, the cost to implement A4 is $2.8*10^5$ USD and for A3 $8.8*10^4$ USD while A1 has already a cost of $2.6*10^6$ USD in this small town. However, this strategy also shows the lowest average resilience performance (11.5) in years and therefore is not favorable in overall.

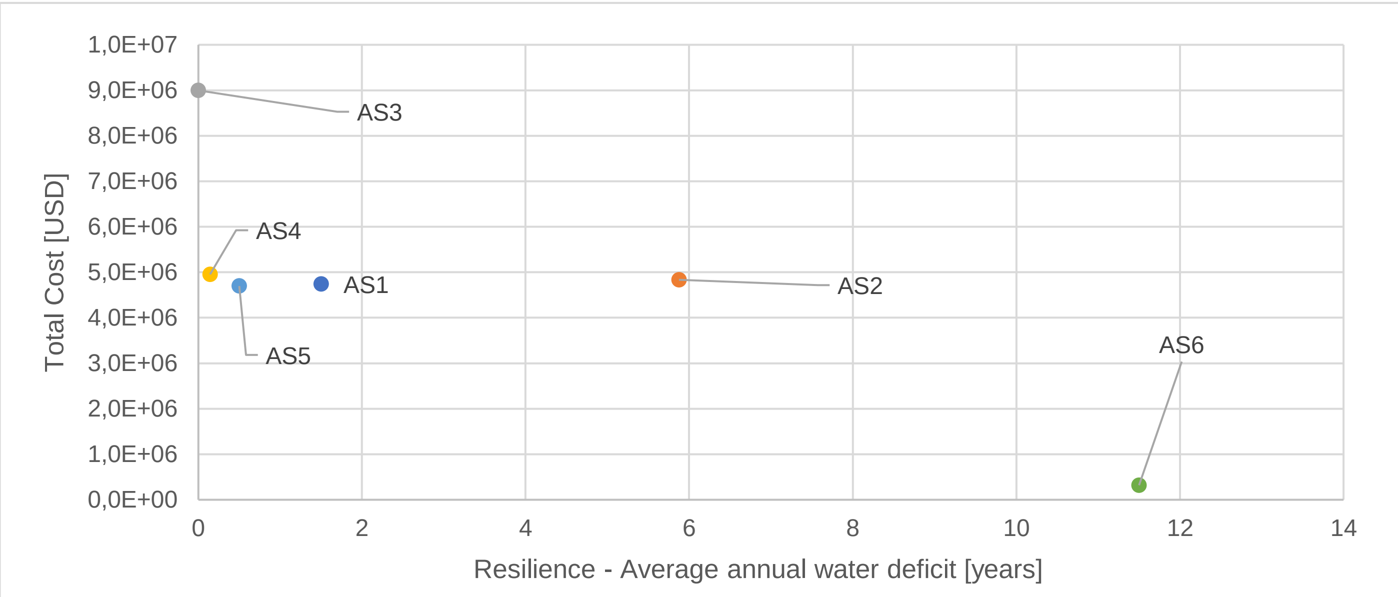

Figure 13: Total cost versus resilience (average annual water deficit in years) graph for intervention strategies for the time-horizon of 2020-2050.

6. Discussion

6.1 Proposed methodology

The approach presented is a multi-objective resilience-based approach to improve the water supply system in the future under uncertainty. Even though the proposed multi-objective approach is promising, there are a few disadvantages to this method. For example, several variables such as population growth and economic growth are assumed to remain constant throughout the planned time-horizon of 30 years, which is unlikely to be the reality. Consequently, the incorporation of variables to be changed over time should be explored.

Furthermore, this thesis proposed a resilience-based methodology where the resilience and robustness are system performances that have been evaluated. However, one can argue that system performances such as reliability (how likely a system is to fail), vulnerability (how severe the consequences of failure might be) and flexibility should be evaluated as well to gain more insight into a comprehensive assessment of the water management system (Beh et al. 2015, Kjeldsen & Rosbjerg 2009) which can be important with regards to long-term water resources planning.

6.2 Suitability of intervention options

The list of intervention options that were used in this thesis should be generally suitable for small towns in Africa. However, one can argue that certain intervention options such as brackish desalination plant might be region specific. Further analysis of different regions in Africa is required to map this out more specifically. Moreover, intervention options considered in different case studies could differ from each other. It might therefore be necessary to consider these options on a case-by-case basis.

6.3 Resilience assessment

In this thesis, the single resilience duration metric has been used to quantify the resilience performance of the intervention options and strategies. Most studies such as Cubillo & Martinez-Codina (2017) and Roach et al. (2018) used a combination of metrics such as the frequency-based metrics with duration-based metrics or volume-based metrics. Frequency-based metrics assess resilience by analyzing the number of water deficit *events* whereas with the resilience duration metric the *duration* of a water deficit is assessed. Since events are less easy, especially in this case-study, to quantify than the duration of the water deficit and it is unable to have a good assessment with these metrics of the impact on the water supply system (Roach et al. 2018), frequency-based metrics are less suitable than the chosen duration-based metrics to provide the best possible information for the decision-makers solutions that represent alternative future pathways to decision makers. Another metrics that could analyze the resilience are the magnitude-based metrics. These metrics assess resilience by analyzing the *magnitude* of the water deficit events. However, one can argue that the *magnitude* of water deficit events may not be that great of a concern to the decision-makers (if it is maintained between acceptable levels) with regard to long-term water resources-planning in comparison to *the duration* of water deficits. Moreover, Roach et al. (2018) found a relatively high correlation between both magnitude-based metrics and the duration-based metrics and therefore mentioned that only the duration metric should be sufficient to evaluate the resilience of a water system.

Volume-based metrics combine the duration and magnitude metrics. These metrics assess the total volume of the water deficit event. There is an uncertainty in the calculation of these metrics which is not favorable since this uncertainty can make it harder to clarify adaption strategies (Roach et al. 2018). Especially, for Sub-Saharan African small towns such as Moamba with the future uncertainties will not be preferable to use the volume base metrics. Since they have a high correlation with duration-based metrics (Roach et al. 2018), it made more sense to use duration-based metrics for this thesis.

The focus in this thesis was on resilience metrics and in particular the duration-based metrics to evaluate the resilience performance of strategies and intervention options. This method is a performance-based approach to analyze the resilience. As mentioned before, the resilience can also be analyzed by property-based methods such as the Graph theory (Diao et al. 2017). The Graph theory is linking the performance of the system with topological attributes such as connectivity and capacity of the water supply. However, this might be an issue for a sub-Saharan African small town due to the unknown interconnection within the water supply system.

6.4 Performances of the individual interventions

The results showed that the intervention options were individually performing low on resilience. Intervention option A2 (Greywater reuse) had the worst resilience performance with a maximum deficit of 30 years. However, it should be noted that the data used for this intervention option in the case-study focused solely on schools and offices, whereas greywater reuse could also be applied to agriculture and households. Therefore, it can be argued that the results for this option are not optimal. Intervention option B1 (Brackish desalination plant) performed the best in terms of resilience with a maximum water deficit period of 3 years. With 62.5%, the robustness of the brackish desalination plant was also higher than the other intervention options. As mentioned before, this can be explained by its potential as an alternative water resource and hence the direct increasing impact on the water supply. However, it should be mentioned that this intervention option also had the highest cost.

When taking a look at how the individual intervention options perform across the different sub-scenarios, it is clear that all of the individual intervention options showed the worst resilience performance in scenario S2a. Since scenario S2 depicts the highest impact on the water supply/demand system, it is not surprising that the worst performance features in this main scenario out of the 3 main scenarios. However, sub-scenario S2a is the dry sub-scenario with upstream-scenario and since it differs in resilience performance in overall with sub-scenario S2d (dry sub-scenario without upstream influences) it is indicated that the variable upstream abstractions a significant role has in the impact on the water supply system. This can be explained by the fact that upstream areas might also economically grow and as a result the water demand will increase as well. This will enhance the water scarcity in the downstream areas.

In general, the acceptable annual resilience performance is zero. Unfortunately, this is not even achieved by the best performing intervention B1. The low resilience performance of the individual intervention options can be explained by their low impact on the water demand or water supply while the gap between the annual water demand and supply grows significantly over time. The resilience performance of the individual intervention options is therefore not acceptable. It is thus necessary to develop intervention strategies to achieve a resilient water supply system in the Sub-Saharan small towns.

6.5 Intervention strategies and preferred solutions

The six intervention strategies are based on addressing the characteristics of the fragile water supply system in small towns with the several options implied by the local drinking water company. This provides insight into the different potential strategies that can be applied in the system. It has been chosen to do this manually for this case-study, while most studies used algorithms and models to show the combination of strategies. It can be argued that if algorithms and models are applied during this stage, a more optimal combination of intervention strategies might be having been found. However, it is assumed that the six intervention strategies will provide different and sufficient possibilities for the decision-makers to create a resilient water supply system.

It is still shown in this thesis that intervention strategies were able to achieve a maximum resilience performance with zero water deficits and a maximum robustness of 100% whereas none of the individual intervention options were able to achieve such a resilience performance or robustness. This shows that intervention strategies can perform better than individual intervention options in terms of both resilience and robustness. This means that by creating intervention strategies by combining different intervention options, not only solutions will be offered to decision-makers that can recover well from the impact from future uncertainties such as climate change (resilience), but these solutions are also strong enough to withstand these uncertainties (robustness). However, though the best intervention strategy showed zero water deficit period, the cost can be a constraint for decision-makers, and it is the question if they would choose a strategy that costs 8.8 million USD for instance in a small African town like Moamba.

Therefore, the implementation of the intervention strategies to create a resilient water supply system depends on the preferences of the decision-makers:

- Decision-makers might select the intervention strategy with the lowest cost solution with a certain target of system performance. This target-based approach could be based on the resilience or robustness. This has been done by other studies such as Roach et al. (2018). For instance, the decision-makers might prefer a robustness of 75% with a low cost-solution. Two strategies AS4 (The support of alternative water source with water loss reduction methods) and AS5 (The blue grey solution with water loss reduction) are strategies with this target level for Moamba. In this case, the AS5 strategy will be selected by the decision-makers due to the lower cost of $4.6*10^6$ USD in comparison with AS4 ($4.9*10^6$ USD). If the decision-makers prefer an annual water deficit below one year, than the AS4 will be preferred due to the lower cost than A3 in Moamba.
- A different approach is to choose the best resilient and robust solution to create a fully resilient water supply system when the cost is not an issue for the decision-makers. For the case of Moamba, the decision-makers will then select AS3 (The support of alternative water sources strategy) as the strategy to improve the system. This strategy has the best resilience performance without any water deficit period with a robustness of 100% as shown in Figure 12 and 13.
- The selection of the intervention strategy with the lowest cost solution might be preferred by the decision-makers when they prioritize the cost as the main objective over resilience due to a limited budget. In the case-study, AS6 strategy then is the most preferable strategy since it has the lowest cost ($3.2*10^5$ USD) across the strategies as shown in Figure 13. However, the resilience performance of this strategy shows an average resilience of 11.5 years which normally would not be acceptable.

- Decision-makers could also select the most cost-effective strategy with a strive to the lowest cost with the resilience performance of zero. In this case, strategy AS4 would be the best solution.

It should be noted that the purpose of the proposed methodology in this thesis is not to suggest a single best solution, but to provide the best possible information on solutions that represent alternative future pathways to decision makers. Selection of the option to be implemented is based on user preferences and should involve input from affected stakeholders.

7. Conclusions

The aim of this thesis was to provide an approach for decision-makers to develop a resilience water supply system in small towns for long-term decision planning. By following the developed resilience methodology for small towns, the future uncertainties such as climate change and rapid urbanization were addressed. This developed methodology provided insight into the multiple plausible futures of the small town and therefore can offer long-term water resources planning.

Based on the results of the case-study, the following conclusions are drawn:

- The presented resilience analysis approach provides a promising method to address future uncertainties and create reliable, long-term water resources planning for small African towns.

- The developed resilience metric shows how well the system performs with the intervention options. The individual intervention options show improvements to create a resilient water supply system. However, the case-study showed that individual options on their own are not able to address well the long-term supply/demand balance as the best individual intervention option still had a maximum water deficit period of 3 years with a robustness of only 62.5%.

- Intervention strategies, consisting of combinations of individual interventions are required to address the problem of long-term water supply/demand balance. These strategies are performing better in terms of resilience and robustness than the individual intervention options which is in overall more feasible and acceptable for decision-makers.

- The multi-objective approach with the two trade-offs between total cost and resilience and robustness and resilience provides insight for decision-makers into different feasible intervention strategies dependent on their own preferences.

Overall, the presented methodology provides a suitable approach to address the long-term demand/supply balance in small towns in Sub-Saharan Africa in terms of a trade-off between the cost of interventions and supply resilience. This method shows the decision-makers an approach to plan and select the best options or strategies to create a resilient water supply system.

8. Recommendations

The developed resilience analysis approach presents a promising method to address future uncertainties and create reliable, long-term water resources planning for small Sub-Saharan African towns.

However, the next recommendations are in order:

- Future research into specific areas and more application of this resilience method on other small towns in Africa is needed to obtain more data about resilience in Sub-Saharan African small towns in general. Specifically, it is recommended to carry out field investigation about the water quality of drinking water and sewage water before dimensioning the greywater reuse system to obtain more accurate data.

- System performances such as vulnerability and reliability should be analyzed as well in other case-studies for evaluating the performance of the water supply system under unsatisfying conditions with resilience. This will improve the resilience assessment and provides more detailed information about the system.

- As mentioned before, the incorporation of variables to be changed over time should be explored more to create a more realistic approach. For instance, the population and economic growth might stabilized in the future. This could be considered in the next steps as well;

- Furthermore, to enhance the impact of the intervention options and the strategies on the analysed water system, it is recommended to involve the important stakeholders and local community and combine their inputs to create the most suitable options.

- The optimization of the interventions or strategies can be improved by using models instead of manually chosen intervention options and system performances such as reliability and vulnerability should be addressed as well to improve the water supply system in small towns.

9. List of references

Al Ge (2010) Renewable and sustainable approaches for desalination. *Renewable and Sustainable Energy Reviews Volume 14*, 2641-2654.

Al SNS (2019) Water Infrastructure Always-In the Making:Distributing Water and Authority through Water Supply Network in Moamba. *Water*, 17.

Al Me (2017) Household Smart Water Metering in Spain:Insights from the Experience of Remote Meter Reading in Alicante. *Sustainability*, 582-600.

Alsulaili A, Hamoda M (2015) Quantification and characterization of greywater from schools. *Water Science & Technology 11*, 1973-1980.

AVK (2020) *Smart Pressure Management.* https://www.avkvalves.eu/en/insights/water-technology/pressure-management

Bank TW (2020) *Greater Maputo Water Supply Expansion Project*.

Beh EHY, Maier HR, Dandy GC (2015) Adaptive, multiobjective optimal sequencing approach for urban water supply augmentation under deep uncertainty. *Water Resour Res 51*:1529–1551, DOI: https://doi.org/10.1002/2014WR016254

Batchelor CF (2011) *Life-cycle costs of rainwater harvesting systems.* The Hague: IRC.

Bowland, C., & Otto, L. (2012). *South African Foreign Policy and African Drivers Programme : Implementing Development Corridors: Lessons from the Maputo Corridor.* Johannesburg: South African Institute of International Affairs. Retrieved from https://www.carecprogram.org/uploads/Maputo-Development-Corridor.pdf

Carden K, Armitage N, Sichone O, Winter K (2010) The use and disposal of greywater in the non-sewered areas of South Africa: Part 2–Greywater management options. *Water SA Vol. 33*, 433-442.

Collins Sistemas de Aqua. (2013). *Cadastro do Sistema de Abastecimento de Água da Vila de Moamba.* Maputo.

Collins sistemas de aqua (local drinking company) (2019). Planilha da Moamba.

Costa NR, Lourenço JA (2015) Exploring Pareto Frontiers in the Response Surface Methodology. In: Yang GC., Ao SI., Gelman L. (eds) Transactions on Engineering Technologies. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9804-4_27

CYPE Ingenieros (2020). *Gerador de Precos Mozambique*. http://www.mocambique.geradordeprecos.info/espacos_urbanos/Instalacoes/Urbanas/Redes_de_agua_potavel/Tubo_de_PVC_0_0_0_0_0_0_0_0_0_3_0.html

De Boer F, Droogers P (2016) Water Allocation Models for the Incomati River. *Report FutureWater*.

Deloitte (2016). Mozambique's economic outlook: Governance challenges holding back economic potential. https://www2.deloitte.com/content/dam/Deloitte/za/Documents/africa/ZA_Mozambique%20country_report_25012017.pdf

Diao K, Sweetapple C, Farmani R, Fu G, Ward S, Butler D (2016) Global resilience analysis of water distribution systems. Water Res 106:383–393. https://doi.org/10.1016/j.watres.2016.10.011

EPA (2015) Systems Measures of Water Distribution System Resilience. EPA 600/R-14/383.

Fazey I, Wise, RM, Lyon C, Campeanu, Moug P, Davies (2016) Past and future adaptation pathways. *Climate and development.*

Farolfi S (2014) Domestic water access and pricing in urban areas of Mozambique: between equity and cost recovery for the provision of a vital resource. *International Journal of Water Resources Development.* 30.

Gerador de Precos Mozambique (2020) *Gerador de preços para construção civil*. http://www.mocambique.geradordeprecos.info/espacos_urbanos/Instalacoes/Urbanas/Redes_de_agua_potavel/Tubo_de_PVC_0_0_0_0_0_0_0_0_0_3_0.html

Godfrey S, Labhasetwar P, Wate S (2009) Greywater reuse in residential schools in Madhya Pradesh, India—A case study of cost–benefit analysis. *Resources, Conservation and Recycling*, 287-293.

Gude VG, Nirmalakhandan N, Deng S (2010) Renewable and sustainable approaches for desalination. *Renewable and Sustainable Energy Reviews Volume 14*, 2641-2654.

Hall JW, Borgomeo E, Bruce A, Di Mauro M, Mortazavi-Naeini, M (2019) Resilience of water resource systems: Lessons from England. *Water Security*, 8, 100052. https://doi.org/10.10.1016/j.wasec.2019.100052

Hashimoto T, Stedinger JR, Loucks DP (1982) Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour Res* 18:14–20. https://doi.org/10.1029/WR018i001p00014

Instituto Nacional De Estatística. (2013). *Estatísticas Do Distrito Moamba.* Maputo.

IWA (2015) *Alternative Water Resources: A Review of Concepts, Solutions and Experiences.* The Hague: IWA.

JICA (2014) *Development of Master Plan for Water Resource Management in Mozambique.*

Jing X, Zhang S, Zang J, Wang Y, Wang, Y (2017) Assessing efficiency and economic viability of rainwater harvesting systems for meeting non-potable water demands in four climatic zones of China. *Resour. Conservat. Recycl., 126* pp. 74-85, 10.1016/j.resconrec.2017.07.027

Kahinda JM, Taigbenu A (2011) Rainwater harvesting in South Africa: Challenges and opportunities. *Physics and Chemistry of the Earth, Parts A/B/C*, 968-976.

Katz D, Grinstein A, Nisan KU (2016) Evaluating fectiveness of a water conservation campaign:Combining experimental and field methods. *Journal of Environmental Management 180*, 335-343. doi:10.1016/j.jenvman.2016.05.049

Khor CS, Akinbola G, Shah N (2020) A model-based optimization study on greywater reuse as an alternative water resource. *Sustainable Production and Consumption 22*, 186–194

Kjeldsen TR, Rosbjerg D (2009). Choice of reliability, resilience, and vulnerability estimators for risk assessments of water resources systems / Choix d'estimateurs de fiabilité, de résilience et de vulnérabilité pour les analyses de risque de systèmes de ressources en eau. *Hydrological Science Journal,* 49.

Macario L, Pedro Simone LM, Hawkins PM (2016) Developing Delegated Management of Small Water Supply Systems: The Emergence of Private Sector Operators in Mozambique. *Conference: Water and Sanitation Program Report.*

March H, Amorote A, Rico Amoros AM, Sauri D (2017) Household Smart Water Metering in Spain:Insights from the Experience of Remote Meter Reading in Alicante. *Sustainability*, 582-600.

Martínez-Codina Á, Cubillo F (2017) A new methodology to measure resilience in water supply systems. *Conference: The IWA World Water Congress & Exhibition 2016*, 1-10.

Matrosov ES, Woods AM, Harou JJ (2013) Robust decision making and info-gap decision theory for water resource system planning. *J Hydrol 494*:43–58. https://doi.org/10.1016/j.jhydrol.2013.03.006

Matrosov ES, Huskova I, Kaspryzyk J, Harou JJ (2015) Many-objective optimization and visual analytics reveal key trade-offs for London's water supply. *Journal of Hydrology 531*.

Matsinhe NP, Juizo DL, Persson KM (2014) The effects of intermittent supply and household storage in the quality of drinking water in Maputo. *Journal of Water Management and Research 70*, 51–60.

Moglia M, Cook S, Tapsuwan S (2018) Promoting Water Conservation: Where to from here? *Water*.

OECD (2017) Social Protection in East Africa: Harnessing the future. OECD publising, Paris. DOI:https://doi.org/10.1787/9789264274228-en

Pagano A, Sweetapple C, Farmani R. et al (2019). Water Distribution Networks Resilience Analysis: a Comparison between Graph Theory-Based Approaches and Global Resilience Analysis. *Water Resour Manage 33*, 2925–2940. https://doi.org/10.1007/s11269-019-02276-x

Quesnel K, Ajami N (2017) Changes in water consumption linked to heavy news media coverage of extreme climatic events. *Science Advances*, 1-9. doi:DOI: 10.1126/sciadv.1700784

Republica de Mocambique Ministerio da administracao estatal (2005) Perfil do distrito de moamba provincial de Maputo.

Roach T, Kapelan Z, Ledbetter R (2018) Resilience-based performance metrics for water resources management under uncertainty. *Adv Water Resour 116*:18–28. https://doi.org/10.1016/j.advwatres.2018.03.016

Roach T, Kapelan Z, Ledbetter R (2018) A Resilience-Based Methodology for Improved Water Resources Adaptation Planning under Deep Uncertainty with Real World Application. *Water Resour Manage 32*, 2013–2031
https://doi.org/10.1007/s11269-018-1914-8

Silva-Novoa Sanchez LM, Kemerink-Seyoum JS, Zwarteveen M (2019) Water infrastructure always-in-the-making: Distributing water and authority through the water supply network in Moamba, Mozambique. *Water 11 (9)* https://doi.org/10.3390/w11091926

Schoen M, Hawkins T, X Xue C, Ma J, Garland NJ Ashbolt (2015) Technologic resilience assessment of coastal community water and wastewater service options. *Sustainability of Water Quality and Ecology*, pp. 75-87.

Silva-Novoa Sanchez et al. (2019). Water Infrastructure Always-In the Making:Distributing Water and Authority through Water Supply Network in Moamba , Mozambique. *Water*, 17.

Srdjevic B, Medeiros YDP, Faria AS (2004) An Objective Multi-Criteria Evaluation of Water Management Scenarios. *Water Resources Management 18*, 35–54.

Smart Pressure Management (2020) *AVK* https://www.avkvalves.eu/en/insights/water-technology/pressure-management

Todini E (2000) Looped water distribution networks design using a resilience index based heuristic approach. *Urban water, 2*, 115-122.

United Nations (2019) Population division world population prospects, Mozambique. https://population.un.org/wpp/Graphs/DemographicProfiles/Line/508

Vuppaladadiyam AK, N Merayo P, Prinsen R, Luque A, Blanco M, Zhao (2018) A review on greywater reuse: quality, risks, barriers and global scenarios. *Environ. Sci. Bio/Tech.,* 18, pp. 77-99

Werner M, Blythe E (2014) User oriented metrics and indicators in water resources decision making.

WHO (2017) Use of basic and safely managed drinking water services. *Global Health Observatory (GHO) data*.

World Bank (2020) Greater Maputo Water Supply Expansion Project. The World Bank.

World Bank (2020) Population Growth (annual %)- Mozambique. The World Bank.

Yazdani A, Jeffrey P (2012) Water distribution system vulnerability analysis using weighted and directed network models. Water Resource Res 48(6):1–10.

Appendix A Area description Moamba

A.1 Climate

Moamba is located at a distance of 75 kilometers from Maputo in Mozambique. The climate of this location is categorized as a semi-arid climate with an average annual temperature of 23 degrees Celsius. Furthermore, (Ministério da Administra rio da Administração Estatal, 2005) stated that two distinctive seasons occur in Moamba. In addition, the rainfall season starts from November until February with an annual rainfall of 570-590 mm and the dry season starts from March to October according to (Ministério da Administra rio da Administração Estatal, 2005).

Moamba experiences the highest precipitation in January with monthly precipitation of 152.4 mm during the rainfall season in 2019. Besides that, the months of June, July and August have a precipitation with less than 20 mm. The lowest average precipitation amounts occur in the month of August with 17.2 mm. The monthly evaporation is unfortunately not measured by the government. However, the annual evaporation has been estimated which ranges between 1433 and 1500 mm in the region.

A.2 River Incomati

The river Incomati is an important water source for Moamba. It provides water for the inhabitants along this river. The Incomati flows from South Africa to the Indian Ocean. The water of the Incomati has been used for many purposes including irrigation and domestic water consumption. It is thus an important water source for this small town and other settlements along this river. The discharge of the river fluctuates by the seasonal climate changes which cause some issues in the surrounding areas. The dry season affects for example the water availability for inhabitants of Moamba. Climate change and rapid urbanization have been noticed by the locals which will affect water availability in the future.

The soil is fertile for agricultural purposes along the Incomati. According to the local government, the soil has clay properties with underneath basalt soil along this river. However, (Bouma, 2020) mentioned that the groundwater has not been used for agriculture or drinking purposes due to the high TDS of 2720 mg/l which is similar to brackish groundwater. Therefore, (Bouma, 2020) stated that groundwater is classified as brackish groundwater. Besides that, the soil in the small town is noticed a sandy-loam soil by the local government.

A.3 Neighbourhoods and Infrastructure

Moamba is built in the colonial period of Mozambique by the Portuguese population according to Silva- Novoa Sanchez et al. (2019). Some colonial buildings and neighborhoods are still used until this day. Currently, this small town has ten Bairro's which is stated by Collins (2019). Yet, seven Barrios are connected to the drinking water supply network. The connected Bairro's are Cimento, Sul, Central, Madinquine, Livine, Matadouro and 25 de Junho (Figure 14).

The neighbourhood of Cimento is built in the colonial period which is assumed due to the grid pattern of this area. It is also assumed that Bairro Cimento is the city centre of Moamba due to various facilities such as local shops, supermarkets, offices, and the local government institutions in this neighbourhood.

Moamba has two important infrastructure intersections. The national roads (N4 and N2) and the railway connect the capital city of Mozambique Maputo with South Africa. Transportation of goods and people towards Maputo and/or South Africa has therefore a significant value for the trade between the two countries. Moamba is thus the main corridor for goods and people in Mozambique to other neighboring countries. Currently, the infrastructure is rehabilitated by the government as part of the Maputo corridor development. Therefore, the accessibility of this small town has been attractive to people and settlements have been increased.

Bairro's	Area [m^2]	Houses	Commercial units	Public units
Matadouro	1589919	675	0	7
Livine	1718212	496	3	2
Madinquine	1357578	385	1	2
Sul	1371381	342	5	4
Central	828748	368	0	2
25 Junho	556384	181	0	4
Cimento	819049	248	30	30

Figure 14: Neighborhoods of Moamba.

A.3 Demographics

Moamba provides accommodation for 24650 residents. As stated by the (Instituto Nacional De Estatística, 2013), the population consists of approximate 51 percent women and 48 percent man in this area. As an observation, a large young population with an age group between 0-14 years old has been noticed in this small town. According to Silva- Novoa Sanchez et al. (2019), major growth in population has been experienced in the last few decades which is caused by the migration of people to this town in the surrounding area. The population increases by 2.1 percent annually (Governmental instituto Mozambique, 2020). This population growth causes issues in this small town. For instance, the settlement of migrants goes along with rising water demand. Therefore, clean water and sanitation will become an important issue in this area.

A.4 Sectors and labor

Agriculture is the main sector in Moamba region with a percentage of 73.9 percent according to (Instituto Nacional De Estatística, 2013). The inhabitants are mainly family farmers who practice extensive and intensive agriculture. The cultivation of vegetables such as maize and bananas are important export products in this town. Likewise, livestock farming contributes to the local economy. The agricultural products of Moamba are mainly transported to Maputo. Besides that, the commercial and service sector is 20.8 percent in Moamba. This sector consists mostly of public services such as schools and the local government. The labour unemployment rate is 36 percent in this area. The local government is stimulating the other sectors in the small town to develop as part of the Maputo Corridor.

A.5 Stakeholders

The water supply system of Moamba has several stakeholders to consider, as shown in Figure 15. It is therefore important to recognize those groups and institutions. Therefore, a small stakeholder analysis has been carried out to gain knowledge about the groups in this thesis.

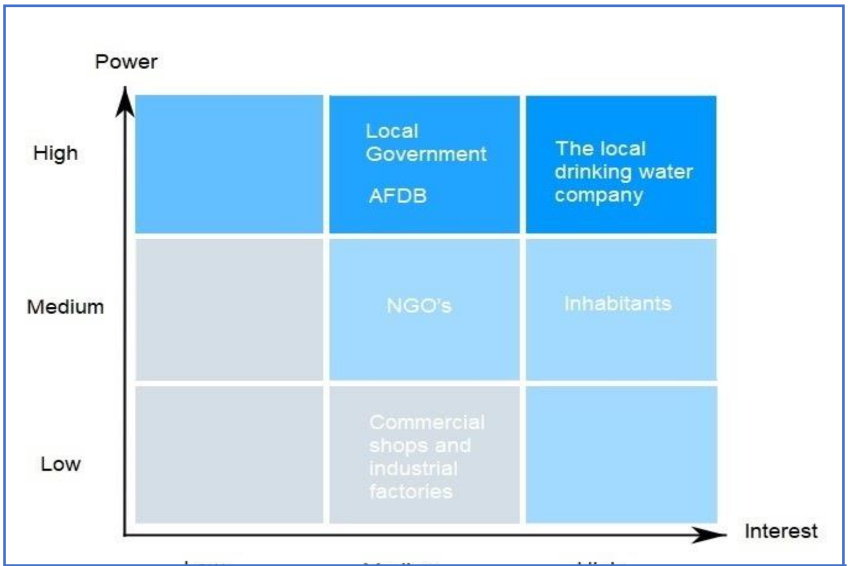

Figure 15: Stakeholders source: (Collins Sistemas de Aqua, 2013) and (Macario, Simone, & Hawkins, 2016)

A.6 Inhabitants

The inhabitants are the main consumers of the water supply system and therefore dependent on the local drinking water company. Their interest is to have sufficient safe clean water which is provided for every person in this small town. Their interest and impact on the water supply are significantly high. Yet their power to improve the system is not high in comparison with the local drinking water company or NGO's.

Water issues are affecting the inhabitants the most which often occur due to certain water supply system deficiencies. According to Silva- Novoa Sanchez et al. (2019), the water supply system is often maintained and extended by the locals without technical experience due to the high cost for the local drinking water company. Hence, the importance to involve the inhabitants is high to create a resilient water supply system.

A.7 Local government

Unfortunately, the information about the local government and their power and interest is scarce. Yet, it is assumed that the local government can stimulate or regulate the local drinking water company by enforcing or adopting policies and laws to improve the water supply system and protect the inhabitants. Furthermore, the public facilities in Moamba are also consumers of the water supply system. The local government has therefore also power and indirect involvement in this water supply system. Their interest is therefore categorized as moderate.

A.8 Commercial shops owners and industry factories

The owners of the industrial factories and commercial shops are also water consumers. Although the information about those sectors is low in Moamba, it is assumed that the interest is to create profit and have sufficient water to use. Hence, the interest is categorized as medium while their power is low in comparison with the other stakeholders.

A.9 NGOs

The construction of this water supply system has been advised and supported by NGOs such as Water for Life and the African Development Bank. The NGOs are mainly contributing to the water supply system by providing financial support and knowledge about operating and constructing the water supply system. Their interest is therefore to provide safe and clean water for the people and achieve to

The African Development Bank encourages the development of many sectors including the water sector in Mozambique. By positioning itself as a financial support institution, the African Development Bank financially supports several water infrastructures projects in Mozambique. For instance, AFDB stated that they provided financial support to the local drinking water company CSA to improve the system or install certain water infrastructure. Mainly, they involve indirectly in projects with the local drinking water company to achieve their goal. Their interest is therefore indirectly, but their power is also high due to the financial support they can grant.

A.10 Water intake, treatment, and distribution system in Moamba

The water supply system in Moamba was built in 2013 according to (Collins Sistemas de Aqua, 2013). Moamba uses the river Incomati as the main water source for the inhabitants. The river water flows through a concrete well with a depth of 3 m. Two pumps are implemented to abstract the river water and store the raw water in a reservoir of 80m^3. According to Silva- Novoa Sanchez et al. (2019) the intake station of river Incomati is 3 km of Moamba.

In 2019, this small town has an annual water abstraction of 679 210m^3. Afterward, the raw water is pumped through a PVC pipe with a diameter of 250 mm to the water treatment facility in Moamba. Coagulation with Iron oxide (III), flocculation, chlorination and filtration are the treatment steps for the raw water (Collins Sistemas de Aqua, 2013). There is also a bypass which is connected with the two water towers. The treated water is stored in those facilities with a height of 31.24 and 19 m. Thereafter, the distributed water flows without valves to the distribution network of the small town with an annual water volume of 554 320 m^3 in 2019. Currently, the billed annually authorized water consumption is 384 046 m^3 (Collins, 2019). The then treated water is stored in two water towers before discharging into Moamba. The two water towers are located in the Bairro of Cimento. The distributed water flows from this location into the seven Bairro's in Moamba. Furthermore, the drinking water pipes are consisting of PVC PN 9 material with a diameter range between 50 and 200 mm. The length of the system is 41.5 km with the pipes that are connected to the intake points for the customers. Besides that, 134 junctions or nodes are noticed in this system. This network is characterized as a dead-end system which is continuous in development. Each year new pipes are connected to the water supply system by inhabitants of Moamba. Those pipes are often man-made. For instance, Silva- Novoa Sanchez et al. (2019) noticed that the man-made pipes in the Bairro Central were often exposed to leakage due to the inexperience of the inhabitants to connect the pipes with the main pipes. Moreover, difficulties in supplying water are also mentioned by the locals due to the elevation in the Bairro Central.

Currently, the network covers the drinking water for nearly 72 percent of the inhabitants in Moamba with an annual billed water volume of 384 046 m^3. (Collins Sistemas de Aqua, 2013) stated that the water supply system has 38849 existing connections, however, it is observed that only 38206 connections were billed in 2019. Furthermore, it is estimated that nearly 6877 people do not have direct access to drinking water in this small town.
The Moamba water supply system is operated by the local private drinking water company Collins Sistemas de Aqua (CSA) which is a water treatment consultancy firm in Mozambique. The local drinking water company constructed this water supply system in 2013. They are responsible for the water supply system that includes maintenance and repairment of this system. However, the local drinking company has a limited budget to repair this system.

As a result of this issue, the water supply system is often poorly maintained. Nonetheless, their interest is to create a fully operating system that provides water for all the inhabitants of Moamba and to create profit. The power, interest and involvement of this local drinking water company are therefore high to consider in this system.

The drinking water facility has an intermittency supply. They provide water between 10:00 to 15:00 according to Silva- Novoa Sanchez et al. (2019). However, the local drinking water company stated that they provide on average 9 hours per day water in 2019. Silva- Novoa Sanchez et al. (2019) stated that intermittence supply is preferred in this town due to several reasons. The main reason why intermittence supply is applied is the influence of interruptions in this drinking water distribution system. Frequently, the abstraction of the river water for electricity for the pumps causes those interruptions.

Leakage and failure in pipes contribute also to the interruption in the system. The local company has to shut down the system to repair the pipes which result in blocking the drinking water supply. Interruptions of 409 hours were observed in the power supply by the local drinking water company (Collins, 2019). Other failures in the system were also observed with 445 hours of interruptions which were not quantified in 2019. This could be the leakage in the water supply system.

Drought is the other reason why intermittence supply is preferred over the continuous supply which is stated by Silva- Novoa Sanchez et al. (2019). A low water table in the river forces the system to abstract less water to the water treatment facility.

This results in a reduction of distributed water to the small town of Moamba. It would not be adequate to provide water for the inhabitants in a continuous system.

A.11 Water consumption of each sector

Five main sectors are connected to the water supply system of Moamba by analyzing the data from (Collins sistemas de aqua, 2019). Each sector has a distinguished water consumption. In general, the domestic water consumption outweighs the water consumption of the other sectors in Moamba. For instance, the domestic sector accounts for the largest billed water supply with a billed water volume of $3.3*10^5$ m^3. This sector has an impact of 85.7 percent on the water distribution network.

Besides that, the public sector has significantly lower water consumption than the domestic sector with seven percent of the Moamba water supply and a billed water volume of 27077. The commercial and the industrial sector have an annual billed water volume of 19239 and 4397 m^3.

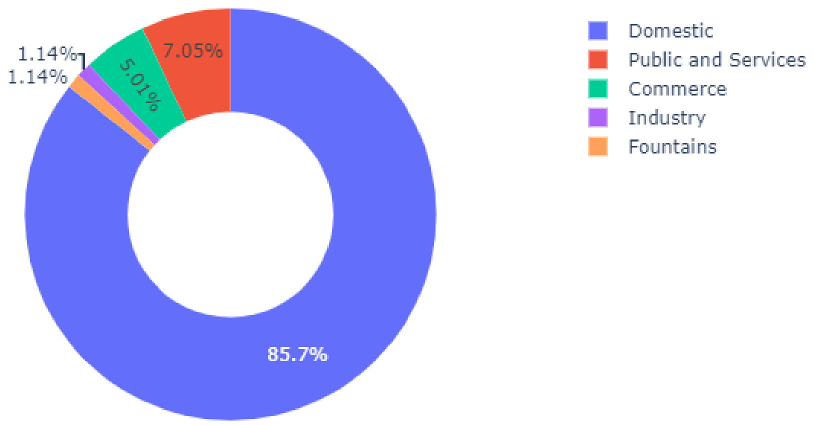

Figure 12 Billed Water Consumption for each sector in percentage (Collins sistemas de aqua, 2019)

Appendix B Calculation of Scenarios

The scenarios illustrate the potential developments of the water demand supply balance in the future. Each scenario has a distinctive impact on the water supply system of Moamba. The water demand and water supply change therefore over time which results in potential water shortage over time. The analysis has been carried out in MS Excel with the changing variables.

Each distinctive variable in the scenarios will have either an impact on the water supply or on the water demand. This is described in the section below.

B.1 Water demand

As said in the previous sections, the water demand is the sum of residential water consumption, non-residential water consumption and water loss. Residential water consumption is calculated by using the formula (3) and (4).

B.2 Population growth

The annual population growth varies between scenarios. For instance, the most likely scenarios use the current population growth of 2.1 %while the flourishing small-town scenarios are assuming a high annual population growth of 3.1 %.

The residential water consumption (*Rwc*) is defined as follows by the population size *Pop* and the daily consumption per capita *dwc :*

$$Rwc\ [m^3/year] = Pop\ [-] * \mathrm{dwc}\ [l/p/\mathrm{d}] \tag{11}$$

Each year the population size will exponentially grow with growth factor or population growth (*GF*) over (*n*) year time: $Pop_{i+1}\ [-] = Pop_i * GF^n$ (12)

B.3 Daily water consumption per capita

Moreover, residential water consumption is also influenced by the daily water consumption per capita. For instance, S2 has an increase of daily water consumption per capita. The baseline value is 46 L/p/d. As said in the previous section, it is assumed that Moamba will have a daily water consumption of 100 L/p/d in 2050 in this scenario. The unit water consumption therefore increases annually with 3.37% for the flourishing small-town scenarios.

It is proposed to linearize the change of unit consumption and the water loss between 2020 and 2050 by using this formula below:

$$\mathrm{dwc}_{i+1}\ [L/p/d] = \mathrm{dwc}_i * change\ of\ percentage \tag{13}$$

Each year, the new daily water consumption per capita (dwc_{i+1}) is increased by using daily water consumption per capita of the year before (dwc_i) with the change of percentage.

B.4 Economic activity

The future projection of the water consumption of the economic sectors are calculated in a similar way. The industrial (*Iwc*), commercial (*Cwc*) , and public water consumption (*Pwc*) of the following years [*i+1*] are calculated by using the growth factor for each consumption and the initial water consumption of the previous year *i:*

$$Iwc_{\ i+1}\ [m^3] = \ Iwc_i\ *\ growth\,factor\ [\%] \tag{14}$$

$$Cwc_{i+1}\ [m^3] = \ Cwc_{\ i}\ *\ growth\,factor\ [\%] \tag{15}$$

$$Pwc_{i+1}\ [m^3] = \ Pwc_i\ *\ growth\,factor\ [\%] \tag{16}$$

B.5 Water loss

It is considered that the baseline for water loss is 32% in 2020. In several scenarios, the water loss is declining or increasing due to the scenario conditions. It is also assumed to use linearization to increase or decrease the water loss percentage. For instance, the flourishing small-town scenarios are considered to meet the target of 10% water loss in 2050. This is converted into an annual percent change of - 2.29% which is implemented in this formula (9).

$$Waterloss_{\ i+1}\ [m^3] = \ water\ loss_i\ \ *\ change\ of\ water\ loss\ [\%] \tag{17}$$

The impact of the water loss has been calculated by multiplying the total residential and non-residential water consumption with water loss percentage.

The annual water demand (*WD*) is calculated by summing the water loss and the total water consumption which consist of the residential, commercial, and public water consumption. This has been done repeatedly for each year until 2050.

$$WD[m^3] = \ Rwc\ [m^3]\ + Iwc\ [m^3]\ +\ Cwc\ [m^3]\ +\ Pwc\ [m^3]\ +\ Waterloss\ [m^3] \tag{18}$$

B.6 Water supply

As an assumption, the water supply is influenced by the change of precipitation and the change of the upstream abstraction for different scenarios. The scenarios without the upstream abstraction are considered to have zero influence of the abstraction. The water availability is depending on the reduction of precipitation or increase which is assumed to be 10% between 2020 and 2100 for scenarios S1 and S3. This is based on De Boer & Drogers (2016). As am assumption, the water availability will increase or decrease with 10% for the S2 scenarios between 2020 and 2050.

$$\begin{aligned}&\text{Change of water availability due to climate change } [\mathrm{m}^3] = \\ &(\text{percentage of reduction water supply in 2050 } [\%]\ /\text{timehorizon } [-]) * \text{t [years]}\ + \\ &\text{Supply } [\mathrm{m}^3]\end{aligned} \tag{19}$$

Appendix C Model structure

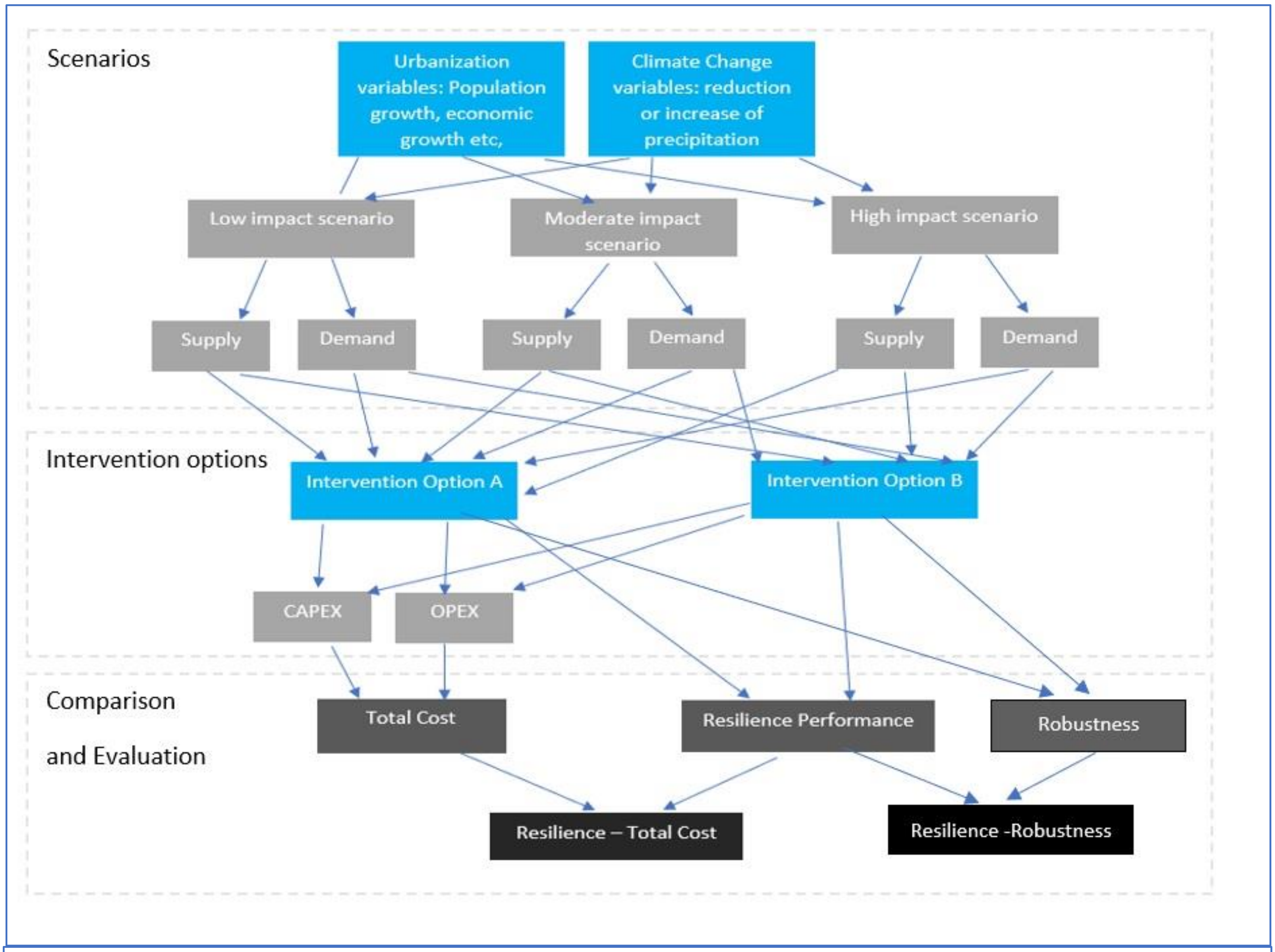

Figure 13: Model structure

Appendix D Calculation of the intervention strategies

The intervention strategies were manually selected, as mentioned earlier, and divided into six different strategies with an impact on the water supply system. In addition, it is chosen to combine the demand and supply scenarios to show the impact on both sides.

The resilience of each intervention strategy is calculated with similar calculations as the individual intervention options. For instance, the supply-based intervention options (*i*) in the strategies are calculated for each supply scenario (WS_{ij}) in equation 21 while the demand-side interventions are reducing the water demand (WD_{ij}) for each demand scenario (*j*) as shown in equation 20.

The impact on water shortage of strategy *x* is calculated by using the sum of the impact of each intervention (*i*) in the strategy *x* as shown in equation 22 In this thesis, eight demand scenarios and eight supply scenarios are analysed with the effect on the intervention strategy.

$$WD_{ij}[m^3/year] = WD_j - impact\ option_i \tag{20}$$

$$WS_{ij}[m^3/year] = WS_j + impact\ option_i \tag{21}$$

$$Water\ shortage_X\ [m^3/year] = \sum_{i=1}^{I} (\mathrm{WD}_{ij} - \mathrm{WS}_{ij}) \tag{22}$$

This cost is added in the CAPEX of the implemented intervention option. The OPEX in the intervention options changes annually and increases linearly. This means that the total cost of the intervention strategy is depending on the duration of the implementation of the intervention options.

The total cost of the intervention strategy of each scenario is thus the combination of the OPEX and CAPEX of the selected combined intervention options. The calculation is also based on the Roach et al. (2018) equation (23) . The year of implementing each intervention option (*ti*) in the strategies differs from the intervention options. Furthermore, the OPEX of intervention (*i*) has been calculated for the time from year 1 to the end of the time horizon T.

$$PV_x = \sum_{i=1}^{I} [\frac{Capex_i}{(1+r)^{ti}} + \sum_{t=1}^{T} \frac{OPEX_i}{(1+r)^t}] \tag{23}$$

The calculation of the robustness for each strategy x has the same approach as the intervention options with the equation (5).