Planning Sustainable Drainage Systems in existing cities in tropical climates

Developing a tool for strategy planning,
design and decision making in flood mitigation plans

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Date of submission: January 15, 2019

Major: Environmental Sciences

Words: 9768 (excluding tables and abstract)

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Abstract

For many years flood mitigation has been approached as a hydraulic problem and solutions were evaluated on their sole capacity to store or drain stormwater cost effectively. In recent years, flood mitigation alternatives, known as Sustainable Drainage Systems (SuDS), have been developed that bring secondary benefits such as heat stress reduction, re-use of rainwater or improve the aesthetics of an area, thus contributing to multiple aspects of a livable city. The variety of available alternatives and their contribution to multiple aspects makes the planning and decision making process complex.

This research analyses the value of Multicriteria Analysis (MCA) as a tool for strategy, planning and design of urban drainage systems and applies this tool to the flood mitigation plans developed for the city of Beira in Mozambique.

The study makes an inventory of available private and public flood mitigation measures along the trajectory from "source to sink" and evaluates the alternatives on multiple criteria and their contributions to social, economic and and ecological aspects of a livable city.

The MCA clearly shows the strengths and weaknesses of the individual alternatives and their possible contribution to the different objectives in creating the desired livable city.

The Multicriteria Analysis tool, used creatively, has proven to be a useful tool that can steer in the design, help in the evaluation of flood mitigation strategies and plans and bring rationality into the complex decision making process.

Key words

Urbanization - Liveable city - Sustainable Drainage Systems (SuDS) - Multi-Criteria Analysis - Masterplan Beira

1 Introduction

Traditionally urban drainage systems have been designed to keep water out of our houses and bring the stormwater as quickly as possible to nearby water bodies (Zhou, 2014). The Sustainable Drainage Systems (SuDS) approach has been proposed as an alternative to more technical, engineering based approaches that solely focus on "keeping our feet dry" (Zhou, 2014). Sustainable drainage approaches are known under different names in different parts of the world. In Europe the term SuDS is commonly used, in Australia Water Sensitive Urban Design (WSUD) and in the United States and Canada Low-Impact Development (LID) (Zhou, 2014).

Urbanization is a process of many small changes in land-use that, if unplanned for, together create larger scale problems such as flooding, health hazards, heat stress and economic, social and environmental losses (Cohen, 2006; Cui & Shi, 2012; Grimmond, 2007; Hollis, 1975). Sustainable Drainage Systems aim to manage surface water drainage in a sustainable manner, taking into account society (People), environment (Planet), and economy (Profit) (Armitage et al., 2013). The focus of the SuDS approach lies on *"..design for water quantity management, water quality treatment, enhanced amenity, and the maintenance of biodiversity"* (Armitage et al., 2013, p.iii). The SuDS approach applies a combination of smaller and larger scale measures that, summed together, aim to solve the drainage problem, while having a positive impact on other problems that come with urbanization, for instance the introduction of green roofs that aim to reduce run-off and heat stress, and wetlands that create open recreational spaces for biodiversity and infiltration ponds that recharge groundwater resources (Bacon, 1997; Valinski & Chandler, 2015).

The SuDS approach has been developed in countries where urbanization usually has taken place in a planned order, regulatory bodies function and proper land development often takes place before building plots are given out. In developing countries, urbanization has often been taking place in a less organized and regulated manner (Cohen, 2006). Public spaces have been occupied overtime, water courses obstructed and space for drainage works is often limited available. In addition, many developing countries are located in tropical climates where rainfall intensity and volumes aggravate the drainage problem. In such a context, a combination of a variety of small and larger scale measures, with integrated secondary benefits, might be a more feasible approach than large scale engineering works.

This research assesses the potential primary and secondary benefits of a SuDS approach in existing cities in developing countries. Primary benefits are defined as the hydrological function of the SuDS approach, secondary benefits are all the other benefits like heat stress reduction, contribution to biodiversity, recreational spaces and tourism.

The research applies the findings to the city of Beira, a flood prone city in Mozambique, where over the past 5 years several flood mitigation plans were developed. The research question for this thesis is defined as:

> *Can a Multicriteria Analysis tool be designed (for Beira) that evaluates flood mitigation plans on the three dimensions of sustainability (people, planet, and profit) and helps in the design and evaluation of the strategy, development of plans and the decision making process?*

In order to answer the research question a series of sub-questions will be addressed:

1. What are alternative measures suggested in a SuDS approach to create storage, reduce stormwater run-off or increase time of concentration and what is their contribution to both flood control and to a more livable city?
2. Which criteria can be used in a comparison tool to assess the different measures of the SuDS approach?
3. How do the different measures of the SuDS approach score relatively to one another per criterion?
4. How do the different alternatives score on the MCA?
5. How will the score of the alternatives change when weights are changed?
6. How can the tool be used to evaluate and improve the design and planning process?

2 The study area: Beira

Figure 1: Geographical location of Beira (Worldatlas, n.d.).

The city of Beira lies along the coast in the centre of Mozambique, a low income country in Southern Africa. Beira is a typical port city in Africa. For almost half a century, since independence in 1975, urbanization took place without proper urban planning, land preparation or expansion of the drainage system. Beira has grown "one house at a time" (van Weelden, 2013). Urbanisation is happening fast. Applying the national population growth rate, observed between 2007 and 2017, the population is expected to grow from 443,469 in 2007 to over 1,134,000 in 2035, over 250% (Instituto Nacional de Estatisticas (INE), n.d.). Large parts of the city are between zero and ten meters above mean sea level. Beira has an average annual rainfall of 1500mm (Bird, 2010), with two distinct seasons: a dry season from May to October and a wet season from November to April. In summer, Beira is exposed to heavy tropical rain storms. Heavy rainfall and urbanization in combination with low altitude, sea surges and poor drainage systems lead to frequent flooding of large parts of the city (van Weelden, 2013).

In 2013 the Masterplan Beira was approved. The Masterplan aims to address the challenges that come with the population growth and by working towards a "*safe, prosperous and beautiful Beira*" (van Weelden, 2013, p. 8). It proposes measures to make the existing city of Beira climate and flood resilient and foresees in a future expansion (see annex) of the city on the higher grounds. The Masterplan suggests to improve the insufficient drainage system in the lower existing city by large scale engineering works. The plan suggests to increase drainage capacity of the existing canals and reserve two areas of 50 hectares for the construction of flood retention basins. The masterplan does not consider Sustainable Drainage Systems (SuDS) as an approach, which given the present land stress could bring multiple benefits.

Since the approval of the masterplan in 2013, at least two more flood mitigation plans were developed for Beira: Greeninfra 4 Beira in 2015 (Kalsbeek, 2015) and Capacity Development Programme Under the Climate Change Adaptation Component in 2017 (Consultancy services for the capacity development programme under the climate change adaptation component, 2018). The Greeninfra 4 Beira plan includes measures of the SuDS approach whilst the Capacity Development Programme Under the Climate Change Adaptation Component does not. Recently in a part of Beira drainage channels were widened and a retention basin was built (Presidência da República de Moçambique, 2018). The decision process in the plan development phase, as well as which plan to follow and which measures to implement is not always clear. This research hopes to contribute to a more comprehensive and rational decision making process that includes all objectives of the masterplan.

3 Methodology

In order to answer the different research questions, several steps were taken. A literature review was conducted to explore the different SuDS measures to reduce peak flows and stormwater volumes while having positive contributions to reduce heat stress, recharge water resources, green spaces, the city ecology and other aspects of a "liveable city"', such as those listed under the Sustainable Drainage Systems (SuDS). This study defines "liveable city" as a city that has a ''high quality of life, competitive economy and sustainable environment" (Centre for liveable cities singapore, 2018, p. 7).

Alternative measures were classified into private and public, according to their location and responsibility for investment. Private measures are on-plot measures and the responsibility of the plot owner. Public measures are measures in public spaces and the responsibility of the City Government.

Measures were further grouped into roofs (source control), rainwater harvesting (source control & re-use), infiltration and detention measures (flood peak reduction, flow reduction & groundwater recharge) and retention basins (flood peak reduction).

A second literature review was conducted in order to choose and design a suitable tool for the sustainability assessment for the different SuDS measures. Ness, Urbel-Piirsalu, Anderberg and Olsson (2007), and Gasparatos and Scolobig (2012) made inventories of the different tools developed for sustainability assessment and their applicability, strengths and weaknesses.

Three tools were identified that could play a role in this research: Cost Benefit Analysis, Impact Assessment and Multi-Criteria Analysis. The *Cost Benefit Analysis* requires costs and benefits to be expressed in monetary units which for this study was considered unrealistic. *The Impact Assessment Tool* is designed for assessing larger projects that have impacts in multiple fields. It is used to predict negative, unintended impacts and take additional measures to avoid or cope with the negative impacts. This study seeks to develop a tool that can help design a flood mitigation strategy and plan based on the the costs and benefits of single drainage measures on multiple criteria. The *Multi-Criteria Analysis* (MCA) is a tool that allows to score single measures on multiple criteria, to assess quantitative and qualitative data, and give stakeholders an insight in the scores and weights and thus the decision making process. Therefore, the MCA was chosen as the most suitable tool for this study.

An MCA requires objectives, each with a number of criteria on which the alternatives are scored. The Beira Master plan sets the objectives to create a "safe, prosperous and beautiful city”, where social, economic and environmental objectives integrate. For each of these objectives, specific criteria were determined, based on the characteristics of the alternative SuDs measures.

Per alternative and for each criterion the score was determined based on findings in literature. Data from field tests were given priority. When no field data were available, deduction, based on the description of the relevant physical processes and parameters, was used. When no academic research was available, e.g. actual pricing, data was gathered from other sources to come to an estimate.

The Multi-Criteria Analysis was conducted on the different measures of the SuDS approach to evaluate the score of each measure. Weights were changed to prioritize between social, economic and environmental objectives and evaluate how prioritization influences the scores and the ranking of the individual alternative measures.

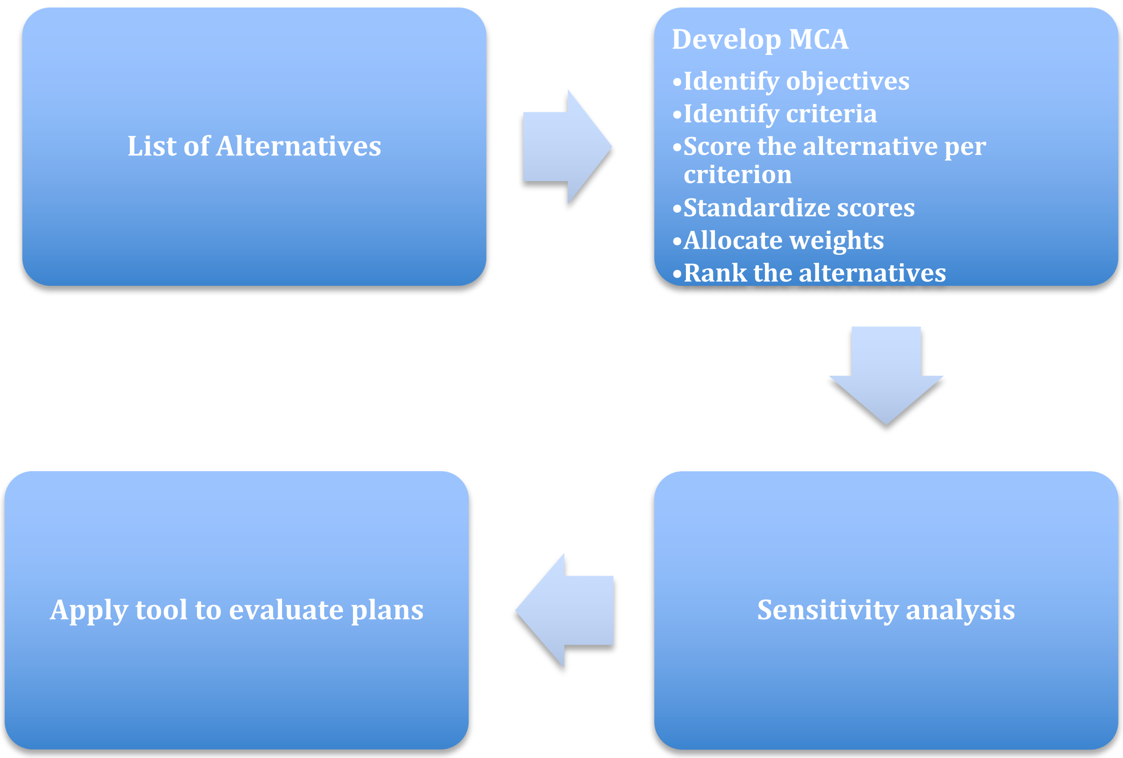


Diagram 1: The process of the MCA

The results of the MCA of the individual measures were then used to evaluate the different flood mitigation plans designed for Beira. The evaluation leads to insights in the planning and decision making process as well as to opportunities for improvement of the strategy and plans.

4 Description of the Alternatives

The alternatives are divided into two groups: Private and Public. Private refers to on-plot measures that are the responsibility of property owners, and public refers to investments in public spaces. The division between private and public is still a new concept found in literature (Stichting Rioned, 2015), but is thought to be an important distinction in the development of plans, since it defines the role of the City Government in implementation. For instance: a rainwater harvesting system is usually an on-plot measure connected to a specific building and the responsibility for the investment and implementation lies in the hands of the owner of the property. The City Government's role is not in financing and building the measures, but in engaging the property owners in the implementation of measures by adopting building regulations or introducing subsidy schemes. On the other hand, drainage channels and water retention ponds are usually located on public soil and their investment, implementation and maintenance are the sole responsibility of the City Government.

The private group consists of roof systems and rainwater harvesting measures. The public group includes public roofs, swales, multi-use detention areas, ponds, retention basins, wetlands, and lagoons.

4.1 Private alternatives

4.1.1 Roofs

4.1.1.1 Blue roof

Figure 2: Blue roof (Mitchell, n.d.)

Blue roofs delay and reduce peak run-off by temporarily storing water on rooftops (Mithraratne, n.d.). The stored water is lost through evaporation and slowly discharging drainage systems (Philadelphia Water Department (PWD), n.d.).

Blue roofs have an estimated storage height between 50mm to 150mm (Roy, Quigley & Raymond, 2014; PWD, n.d.). In order to store $1m^3$ of water, a blue roof of storage height 0.15m and an area of $6.7m^2$ would be required.

A blue roof, as a control at the source, does not have a major positive effect on the water quality. The fresh rainwater is only polluted by small particles it collected from the air. Therefore the cleaning effect of blue roofs is limited.

Many flat roofs can easily be converted into blue roofs using simple technology and at low investment and maintenance costs. Especially in Beira's business centre many buildings have flat roof tops and the installation of blue roofs is considered a possibility. The total amount of storage that can be created on blue roofs is however limited by the total area of suitable flat roofs in the existing and future city.

4.1.1.2 Green roofs

Green roofs, are vegetated rooftops that reduce rainfall run-off by absorbing water in porous soils (Mentens, Raes & Hermy, 2006). There are two types of green roofs: intensive and extensive green roofs. Intensive green roofs have a deeper soil layer and a "higher" vegetation. According to Berndtsson (2010) water retention and run-off in green roofs depends on the characteristics of the green roof and weather conditions. Characteristics include soil thickness and type, vegetation cover and type, and the geometry of the roof (slope, length, position, and age). Weather conditions that affect the storage capacity and run-off include the length of the dry period and rainfall characteristics (intensity and duration) (Berndtsson, 2010). Chai, Putuhena & Selaman (2017) found that the retention rate decreases with increased rainfall depth, which may make green roofs less effective in tropical conditions with high rainfall depths.

The theoretical storage capacity (SC) of a Green Roof in m^3/m^2 can be found by the following formula (Speak, Rothwell, Lindley & Smith, 2013):

$$SC\ (m^3/m^2) = WC\ (\%) \times SH\ (m)\ ,$$

where

SC = Storage Capacity (m^3/m^2)

WC = Water Capacity (%) = Field capacity of a soil (%) - wilting point (%)

SH = Substrate Height (m)

This theoretical storage capacity is found under laboratory conditions. Under field conditions, Speak et al. (2013) found a maximum storage capacity of only 45% of the theoretical storage capacity. This study introduced a field factor to estimate the Storage Capacity under field conditions from the theoretical Storage Capacity. The field factor was set at 45%.

With respect to water quality, green roofs are a bit better than blue roofs, due to its filter working, but the difference is minimal since both measures are located at the source and the rainwater is not yet polluted by the run-off process.

Intensive green roofs can serve as roof gardens that add to the biodiversity and green spaces in a city (Oberndorfer et al., 2007). Their vegetation allows for heat stress reduction (Hien, Yok & Yu, 2007; Mentens et al., 2006; Takebayashi, Moriyama, 2007).

Intensive green roofs are, like blue roofs, limited to flat roof areas whilst extensive green roofs are not. Green roofs are technically more complicated and financially more costly in both investment as well as maintenance (Foster, Lowe & Winkelman, 2011; Peck & Kuhn, n.d.).

Figure 3: Intensive green roof (Rainways, n.d.)

4.1.1.2.1 Intensive green roofs

Intensive green roofs have a relatively thick soil layer greater than 0.15m (Chow & Bakar, 2016; Speak, et al., 2013). This study uses an intensive green roof with a height of 0.20m in its comparisons. According to Oberndorfer et al. (2007), the only plant restrictions are those based on substrate depth, climate, building height, and irrigation facilities.

Intensive green roofs can be located on private houses and buildings where they are not accessible to the public or on buildings where they are accessible to the public. Since the two forms score differently on the criteria of "recreational space", two different alternatives were introduced in the MCA: intensive green roofs on private rooftops and intensive green roofs on rooftops accessible to the public.

4.1.1.2.2 Extensive green roofs

Figure 4: Extensive green roof (Access irrigaton, n.d.)

Extensive green roofs have a soil layer smaller than 0.15m (Chow & Bakar, 2016; Speak, et al., 2013) and have typically low growing vegetation (plants and mosses) (Oberndorfer et al., 2007). Stormwater retention capacity is smaller because of the lesser depth of its substrate. This study applies an extensive green roof with a height of 0.15m.

Extensive green roofs are considered to perform similar to intensive green roofs in processes like reducing heat stress and water quality.

4.1.1.2.3 Blue-green roof

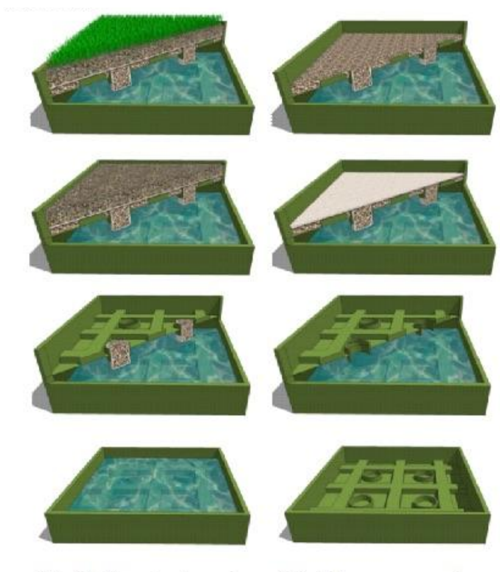


Figure 5: Blue-green roof (Shafique, Kim & Lee, 2016)

A Blue-green roof is a combination of both: the green and the blue roof (Shafique, Kim, & Lee, 2016). The vegetated green roof is on top of the blue roof as shown in figure 5. This concept allows more water to be stored in the case of a flooding event, while maintaining a function in heat stress reduction and water quality.

This study assumes a blue-green roof as a combination of a blue and an *extensive* green roof. Technically the blue-green roof is more complicated to install and maintain than green roofs and blue roofs.

Due to the lack of data on blue-green roofs, the same formulas for *extensive* green roofs and blue roofs were used to determine the hydrological performance.

4.1.2 Domestic rainwater harvesting

Domestic rainwater harvesting (DRWH) is the process whereby rainwater is collected from rooftops, courtyards and compact or treated surfaces, and stored in underground or aboveground tanks (Kahinda, Taigbenu & Boroto, 2007). DRWH allows underserved areas to have access to water (Kahinda et al., 2007; Worm & van Hattum, 2006), thereby reducing water scarcity (Helmreich & Horn, 2009). This study evaluates three different types of DRWH measures: the standard rainwater harvesting dam, rooftop rainwater harvesting with aboveground storage tanks and rooftop rainwater harvesting with underground storage.

Rainwater harvesting measures are not considered to have an effect on heat stress, biodiversity and water quality. They score positive on the potential to re-use water and since the storage tanks are located on the private plots it will not lay a claim on land resources.

4.1.2.1 Standard rainwater harvesting dam

Figure 6: Standard rainwater harvesting dam (Department of Water Affairs and Forestry, 2007)

According to the Department of Water Affairs and Forestry (2007) the standard rainwater harvesting dam is an underground tank made from cement, with a proposed depth of 2m and a storage capacity of 30m^3.

In Mozambique it is compulsory for most housing to have a septic tank. The technology for a septic tank is not very different to that of a rainwater harvesting dam. The standard rainwater harvesting dam, like a septic tank, could be made compulsory by the City Government and could be placed under a driveway, which on average has a width of 3m (Cohen, n.d.).

4.1.2.2 Rooftop rainwater harvesting with underground storage tanks

Figure 7: Rooftop rainwater harvesting with underground storage (Builders, n.d.1)

Rooftop rainwater harvesting (RRWH) collects water from rooftops, and stores the water in underground tanks for future use (Dwivedi & Bhadauria, 2009). To store 1m^3 of stormwater, the underground storage tank requires a height of 2m and needs an area of 0.5m^2. (Builders, n.d. 1)

4.1.2.3 Rooftop rainwater harvesting with aboveground storage tanks

Figure 8: Rooftop rainwater harvesting with aboveground storage (Builders, n.d.2)

The principle of RRWH with aboveground storage is the same as that with underground storage tanks. However, RRWH with aboveground storage tanks are easier to implement as sand does not need to be dug out in order to install the aboveground tank. The dimensions of the aboveground RRWH storage tank are equivalent to that of the underground storage tank.

4.2 Public alternatives

4.2.1 Infiltration and detention

4.2.1.1 Permeable pavement

Figure 9: Permeable pavement (Paver search, n.d.)

Permeable pavements allow stormwater to infiltrate into the underlying soil, leading to run-off reduction and hydrograph attenuation (Beecham, Lucke & Myers, 2010; Marchioni & Becciu, 2015). Two types of permeable pavements can be distinguished: pavements designed and installed with the objective to infiltrate and store water and pavements designed for water harvesting and reuse (Beecham et al., 2010; Marchioni & Becciu, 2015). This study uses the former as an alternative for comparison.

The hydrological performance and storage capacity differs based on the characteristics of the pavement and underlying soil layers. Park, Sandoval, Lin, Kim & Cho (2014) calculated the storage capacity under a typical permeable block pavement at 42.55 l/m^2. For the purpose of this study, this value has been used. The hydrological performance is also found to be highly dependent on maintenance (van Duin, Brown, Chu, Marsalek & Valeo, 2008; Marchioni & Becciu, 2015).

The effect of permeable pavements on water quality has been found considerable by various studies. Contrary to roof run-off, pavement run-off is polluted with solid sediments, fuel, oil, grease and metals. Several studies found that the infiltration process trapped solid sediment and other pollutants in the pavement layers, while no contamination was found in the underlying soil (Brattebo & Booth, 2003; Legret, Colandini & Le Marc, 1996).

4.2.1.2 Swales

Figure 10: Swales (n.a., n.d.)

Swales are grass-lined channels that can store, transport and infiltrate stormwater (Charlesworth, Harker & Rickard, 2003). The benefits of both engineered soil and native soil swales were compared in this study.

The engineered soil swale used in this study is made from S1 surface layer soils and S3 drainage layer soils (Valinski & Chandler, 2015). According to Hopper (2007), S1 surface layer soils are made from medium loamy sand and organic matter and S3 drainage layer soils are made from gravelly sand which allows water to flow through at a high rate. The native soil swales in this study are made from native silty loam. The engineered soil swales score better on the recharge of groundwater and storage capacity than native soil swales.

Swales improve stormwater quality by two processes: sedimentation and filtration (Stagge, Davis, Jamil, & Kim, 2012). Sedimentation occurs when water is trapped in the swale, above the soil and filtration occurs when the stormwater seeps into the soil trapping solid sediments and other pollutants.

Swales can contribute to the aesthetics, biodiversity and heat stress reduction in an area (Pille & Saeumel, 2016; Polypipe, (n.d.).

4.2.1.3 Multi-use detention area

A multi-use detention area refers to an area that is not exclusively reserved for flood mitigation. For a large part of the year, the area serves another purpose in the neighborhood, like a football pitch or green space. Two different types of detention areas are considered: bare soil and green multi-use detention areas.

The bare multi-use detention area used in this study is suggested in the Greeninfra 4 Beira plan (Kalsbeek, 2015). Normally it serves as a neighborhood football pitch, but is dug out roughly 0.5m, and storm water is drained towards the pitch and retained on the pitch, until it is evaporated or infiltrated.

Figure 11: Bare soil muilti-use detention area (Kalsbeek, 2015)

In contrast to the bare soil detention area, the green multi-use detention area is a specially designed green space and requires a higher investment than the bare soil alternative.

Figure 12: Green multi-use detention area (Landzine, n.d.)

The dimensions of the green multi-use detention area are the same as for the bare soil multi-use detention area. The average height of 0.5m was based on the storage depth observed in wetlands (Sun, Saeed & Zhang, 2013). In order to store $1m^3$ of water, a surface area of $2m^2$ is needed.

In both the multi-use detention areas water quality is improved through sedimentation, filtration and infiltration. The green multi-use detention area is assumed to contribute to aesthetics, biodiversity and heat stress reduction like the swales and intensive green roofs (Hien, Yok & Yu, 2007; Mentens, Raes & Hermy, 2006; Oberndorfer et al., 2007; Pille & Saeumel, 2016; Polypipe. n.d; Rozos, Makropoulos & Maksimović, 2013; Takebayashi, Moriyama, 2007).

4.2.1.4Dry detention pond

Figure 13: Dry detention pond (Suckers, 2015)

A dry detention pond is focused on the temporary storage of stormwater run-off (Lai, & Mah, 2012; Hussain, Brand, Gulliver & Weiss, 2006). In a detention pond, water is initially stored aboveground and can then infiltrate through into the soil (Figure 13). In contrast to the multi-use detention area, its main purpose is not recreational space, but stormwater retention. Therefore the dry detention pond is usually deeper, and its vegetation is limited to grass.

Water quality is improved in the same manner as the multi-use detention areas, and the area also contributes to aesthetics, biodiversity and heat stress reduction (Getter, Rowe, Robertson, Cregg & Andresen, 2009; Pille & Saeumel, 2016; Polypipe. (n.d.).

4.2.1.5 Wet retention pond

Figure 14: Wet retention pond (Susdrain, n.d.2)

A wet retention pond, like the dry detention pond temporarily stores stormwater run-off. In contrast to a dry detention pond, a wet retention pond is a basin where a minimum water level and flow are guaranteed (Barrett, 2004). The minimum water level and flow allow for a different aesthetics, heat stress reduction and some aquatic life forms (Gunawardena, Wells & Kershaw, 2017; Susdrain, n.d.2). The wet retention pond has a function as a hydraulic feature as well as a landscape feature.

A wet retention pond can be seen as a mini lagoon in a neighborhood. It serves many of the same objectives and shares many of the same characteristics, but it is a much smaller measure, with less implications on e.g. resettlement, and it can be implemented on a neighborhood scale.

Retention ponds, being open water bodies that do receive run-off from other areas do not have a particular positive effect on the water quality. However, sedimentation of the suspended solids will take place.

4.2.1.6 Retention basin

Figure 15: Recently constructed retention basin in Beira (Portalmoz news, 2017)

The prime purpose of a retention basin is to collect and store stormwater run-off (Waelti & Spuhler, 2018). A retention basin always holds water (Waelti & Spuhler, 2018).

In this study a retention basin with a sealed bottom is used which inhibits infiltration and groundwater recharge. Instead, the collected stormwater is stored for future use.

A study in Mozambique proposes retention basins with a maximum storage depth of 3m (Consultancy services for the capacity development program under the climate change adaptation component, 2018), which is considered to be the maximum storage depth of the retention basin used in this study.

A retention basin is designed to have a hydraulic purpose and not a landscaping purpose. Therefore, retention basins do not contribute to the aesthetics or biodiversity. The only active process to improve water quality is sedimentation.

4.2.1.7 Wetlands

According to Junk et al. (2014) wetlands are "ecosystems at the interface between aquatic and terrestrial environments; they may be continental or coastal, natural or artificial, permanently or periodically inundated by shallow water or consist of waterlogged soils. Their waters may be fresh, or highly or mildly saline. Wetlands are home to specific plant and animal communities adapted to their hydrological dynamics" (p. 12). Brix (1994) simplifies the definition to wetlands with soils that are periodically somewhat saturated.

The ability of wetlands to be wet periodically, makes wetlands an option for flood mitigation. Wetlands can store approximately 0.5m of surface water and thus need an area of $2m^2$ to store $1m^3$ of stormwater (Sun, Saeed & Zhang, 2013).

Figure 16: Wetland (The wetlands initiative, n.d.)

Sedimentation that occurs in wetlands contributes to the improvement of water quality. Wetlands also contribute to the biodiversity, aesthetics and reduction of heat stress (Bacon, 1997; Gunawardena, Wells & Kershaw, 2017; Junk et al. 2014; Susdrain, n.d.3). Wetlands have limited capability to sequester CO_2 and are emitters of the greenhouse gas methane (Brevik & Homburg, 2004; Devol, Richey, Forsberg & Martinelli, 1990).

4.2.1.8 Lagoon

Figure 17: Lagoon (Florida state parks, n.d.)

Besides their hydraulic function, lagoons have an important function as recreational space for the city as well as for the development of tourism. The *Greeninfra 4 Beira* plan foresees in a lagoon with a maximum storage depth of 1.4m, meaning that a 0.71 m^2 of lagoon area is needed to create 1.0m^3 storm water storage (Kalsbeek, 2015). However, it must be noted that the lagoon is located far downstream and therefore only functions in combination with a proper drainage canal system.

Water quality in a lagoon is improved through sedimentation, dilution as well as biological cleaning of pollutants (Macek, et al., 2004). A lagoon also contributes to biodiversity, aesthetics and reduction of heat stress (Gunawardena, Wells & Kershaw, 2017; Kalsbeek, 2015).

5 The MCA

The process of the MCA was derived from van Herwijnen and Janssen, (2004). The criteria, standardisation of scores, weights and rankings applied in the MCA are described below.

5.1 The criteria

The flood mitigation measures are an integrated part of the Beira Masterplan which sets the goal to create a "*safe, prosperous and beautiful Beira*" (van Weelden, 2013, p. 8). This translates into social, economic and environmental objectives of the City Government which are further detailed in the Masterplan. Objectives include among others the improvement of the living conditions of the citizens of Beira, the development of the coast and coastal plains for biodiversity and tourism, and the growth of the traffic in the Beira harbour (van Weelden, 2013).

The three main objectives are further divided into criteria, categorized in costs and benefits, each with their own scale and weight. Criteria were derived from the characteristic of the SuDS measures found in the literature review and the specific objectives for the city of Beira derived from the Beira Masterplan.

In order to make all values comparable, the creation on $1m^3$ of stormwater storage was taken as the common factor.

5.1.1 Social objectives

Four criteria were identified in the social objectives: Resettlement, aesthetics and recreational space for the city and in the neighbourhood.

5.1.1.1.1 Resettlement

Resettlement is a social cost. Drainage interventions might imply resettlement. Negotiations on compensation and land acquisition for relocation can be complex, costly and time consuming processes. When people are resettled far away from their current home and cannot continue their present lifestyle, resettlement is not a simple relocation, but a total social and economic transformation of a population.

However, this does not necessarily need to be the case. In Mozambique's capital Maputo there are initiatives where people are resettled within their own neighbourhood, e.g. by transforming multiple houses into an apartment complex in the same neighbourhood, space becomes available to redesign poorly laid-out neighbourhoods that have been constructed without any form of planning for roads, drainage and green spaces. The introduction of SuDS measures will have a positive effect on the ecological and social aspects and increase the economic value of the plots in the neighbourhood.

Small scale SuDS measures require less people to resettle and are more likely to find a solution in the neighbourhood. Large scale measures require more people to resettle and are more likely to relocate people far from their present homes, leading to higher social costs. SuDS measures that do not require resettlement are scored 0, small scale measures score 1, large scale measures score 2.

5.1.1.2 Aesthetics

Measures of the SuDS approach can have a positive effect on the aesthetics of an area. Whether one alternative is more aesthetically pleasing than the other is very subjective. Aesthetics is scored on an ordinal scale: either it is meant to be aesthetically pleasing (2), it blends in (1), or it imposes itself negatively upon the aesthetics of the area (0).

5.1.1.3 Space for recreation

Two different criteria have been created in order to asses the space for recreation SuDS measures bring into an area: space for recreation for the city, and space for recreation in the neighbourhood.

The former is referring to recreational spaces that have a function for the city as a whole, like a beach front or a central park, the latter to spaces that have a function for the neighbourhood only.

Whether measures of the SuDS approach remove or create an area that can be used for recreation is identified with this criteria in ordinal scale (0 - 1). Measures that occupy space solely for the purpose of flood mitigation score "0", measures that allow for a multi-functional space like combining flood mitigation and recreational use score "1".

5.1.2 Ecological objectives

Six criteria were identified in the ecological objectives: reduction of heat stress, increase in biodiversity, reduction of greenhouse gasses, emission of greenhouse gases, recharge of groundwater and improve water quality.

5.1.2.1 Reduction of heat stress

Urban areas, with lots of concrete, tarmac and pavements generally have higher air temperatures than rural areas. The stone surfaces absorb the heat during the day and emit the heat at night, while the cooling effect of evapotranspiration by vegetation is less (Santamouris, 2013).

The cooling effect of SuDS measures is considered beneficial for a tropical city. There is however, limited quantitative data available on the effect different measures have on reducing heat stress. This study scores the reduction of heat stress by first scoring on an ordinal scale (0-2) the potential for heat stress reduction and then multiplying that by the surface area required to store $1m^3$ of storm water. Zero (0) stands for no reduction, 1 when heat stress reduction is a secondary benefit and 2 when heat reduction is a major benefit.

5.1.2.2 Increase in biodiversity

Biodiversity is defined as "the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (Convention on biological diversity, 2007).

Habitat loss and fragmentation are one of the lead causes of extinction and elimination of native species (Kruess, Tscharntke, 1994; McKinney, 2002; Czech, Krausman & Devers, 2000). Creating habitat increases biodiversity. Increased biodiversity in combination with green spaces has a positive effect on the health and well-being of humans (Gemeente Amsterdam, 2011).

Some SuDS will increase biodiversity at microbiological level, others at macrobiological. There are no studies that evaluate the increase in biodiversity on all levels for all alternatives. Therefore, biodiversity increase is expressed on the ordinal scale (0-2); the alternative either decreases biodiversity (0), keeps it alike (1), or increases biodiversity

(2), compared to a non-built area.

5.1.2.3Reduction of greenhouse gas

The reduction of Carbon (C) is used as a proxy for Photosynthesis which is the process responsible for sequestering CO_2 (equation 1).

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \quad (1)$$

The ability to sequester CO_2 is given in grams/year. When field data are lacking, the Carbon sequestration is believed to be the same as in extensive green roofs when processes are similar.

5.1.2.4 Emission of greenhouse gas

Methanogenesis (equation 2) in soils, driven by microbial activities, is the process responsible for the production of methane (Le Mer & Roger, 2001).

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 \quad (2)$$

The produced Methane is released into the atmosphere through *"the aerenchyma of aquatic plants, but also by diffusion and as bubbles escaping from wetland soils."* (Le Mer & Roger, 2001, p. 25). Methane emissions are expressed in grams/year. When no data was available, Methane emissions from the tropical savanna were used for similar processes.

5.1.2.5 Recharge of groundwater

Fresh water is an important resource and groundwater recharge is important in reducing surface run-off and combating water scarcity (Harbor, 1994). The maximum groundwater recharge depends on the depth of the groundwater level. In Beira the average water ground water level is at -148cm below surface level (Simon, 2015). Allowing a maximum groundwater level of -48cm for a short time, a maximum groundwater level rise of 100cm is possible.

Recharge is further dependent on the infiltration rate of the (applied) topsoils and the natural subsoil. In the MCA effects table groundwater recharge is given in mm/hr.

5.1.2.6Improve water quality

Water quality is defined as the quality of the open water bodies. The open water bodies are fed by storm water run-off, thus the more polluted the storm water run-off, the higher the pollution of the open water bodies. The pollution of the storm water reaching the open water bodies is influenced by pollution and cleaning processes. The scores of the two processes are summed and divided by two to reduce the score range.

5.1.2.6.1 Pollution process

Stormwater is initially polluted by collecting pollution particles out of the air as it makes its way to the Earth's surface. Once the stormwater reaches the surface and turns into surface run-off it collects other pollutants such as dust and oil. The higher the run-off velocity, the more pollution the stormwater can carry (Johnston, 1991). The surface run-off travels to the receiving water body, polluting the open waters.

The pollution process is "graded" in the MCA by two processes: whether or not the run-off speed is reduced and where in the run-off process the SuDS measure is. Measures of the SuDS approach that decrease run-off speed and thus collect lower amounts of pollution score a 1, others score 0. For its position in the run-off process, a measure closest to the source scores a 3, whilst measures closest to the receiving water body score 0. The two scores are then multiplied since they reinforce each other.

5.1.2.6.2 Cleaning process

Water can be purified through three different processes: sedimentation, filtration and infiltration. Sedimentation occurs when water slows down or stands still. Larger particles are removed by gravity reducing the turbidity and concentration of suspended solids in surface waters (Johnston, 1991). Filtration removes particles by leading water through a porous layer. Filtration delays surface run-off. Infiltration removes the rainwater from the run-off system. The infiltrated rainwater only flows back into the open water system through underground flow.

Infiltration has the best cleaning ability and is therefore represented with a score of 3, followed by filtration (2), sedimentation (1) and no cleaning process (0).

When a SuDS measure is close to the source, like green roofs, the cleaning processes (filtration) will be less effective since the rainwater has collected little pollution. Swales on the other hand, that collect run-off water from street surfaces, have a larger effect on the water quality. Therefore the sum of the score of the different cleaning processes is multiplied by the position of the measure in the run-off system. Measures close to the source receive a score of 1, while measures further downstream receive a score of 3.

5.1.3 Economic objectives

Five criteria were identified in the economic objectives: land acquisition, investment, maintenance costs, water harvesting and tourism.

5.1.3.1 Land acquisition cost

Land acquisition costs are only considered when single-use surface area on public soil is required. Measures on rooftops, underground measures, measures on private plots as well as multi-use areas do not increase the demand for land area and thus do not need any land acquisition. Land acquisition costs are expressed as the costs of land per m^2 multiplied by the area needed to store $1m^3$ of water.

5.1.3.2 Investment

Cost estimates vary significantly depending on the specific design of the alternative. The average price of different alternatives used were converted to Euros.
The investment costs showed a wide range. Ten out of eighteen alternatives fit within a price range of below €100 per m^3 storage created; eight alternatives are in a price range of €100-12000. Applying a maximum scale would compress the lower cost alternatives too much, therefore alternatives were ranked and an ordinal scale was used.

5.1.3.3 Maintenance cost

Maintenance costs are important. Average maintenance costs found in literature were used. In the absence of data on maintenance costs, maintenance costs were assumed to be 2% of the investment costs, which is an accepted figure in many civil works maintenance estimates (Pennsylvania Stormwater Management Manual: Section 5 - Structural BMPs, n.d.; van Weelden, 2013; Kalsbeek, 2015). Like the investment costs, a relative ranking and an ordinal scale was used.

5.1.3.4 Water harvesting

Water harvesting (m^3) is the amount of stormwater that can be stored for later use. The harvested water reduces stormwater run-off and increases water availability. In times of water scarcity, harvested water plays an important role. If a measure is designed to harvest water it is given a score of $1m^3/m^3$ storage, if not the score is $0m^3/m^3$ storage.

5.1.3.5 Tourism

Measures of the SuDS approach that can generate income through tourism, like the 150 ha lagoon proposed in the Greeninfra 4 Beira plan, may make its implementation more financially feasible. If an alternative can generate an income through tourism it receives a score of 1, if not, it receives a score of 0.

5.2 Standardizing scores

In order to convert the scores on multiple criteria on various scales into one score, the scores need to be standardized to one common dimension. Scores are standardized by means of the "maximum standardization" equations or "interval standardization" equations. (Table 1). Maximum standardization is used when hard quantifiable data are available. Maximum standardization uses the relative distance between zero and the maximum performance to standardize the score. The interval standardization is used when only relative scores are available, or when the hard quantifiable data show a very wide range. The method standardizes the scores of the alternatives based on the relative position on the interval between the highest and lowest performance.

The standardization equation used depends on whether the criteria is a cost or benefit.

	Maximum standardization	Interval standardization
Cost	$1 - \frac{score}{highest\ score}$	$1 - \frac{score - lowest\ score}{highest\ score - lowest\ score}$
Benefit	$\frac{score}{highest\ score}$	$\frac{score - lowest\ score}{highest\ score - lowest\ score}$

Table 1: Equations to determine the new, standardized scores (van Herwijnen & Janssen, 2004)

5.3 Weights

The weights allocated to each criteria are subjective in nature and are subject to change according to priorities and the main objectives of a plan. In an urban planning process initial weights could be attributed by city planners, while final weights could be the outcome of a stakeholder discussion.

As an initial approach, this research chooses not to favour between the three overall objectives (ecological, economic and social). All three were attributed an equal weight of 33.33%. Weights of the overall objectives were then changed to prioritize different objectives in a sensitivity analysis (see sensitivity analysis).

Within each main objective, individual criteria were weighted relative to one another on a scale of 10-50. The actual weight of each criterion is than calculated with the following equation:

$$AW_i = \frac{RW_i}{R\sum_{i=1}^{i=n} RW_i} \times W_o \quad (3)$$

Where:

AW_i = Actual Weight of the criterion i

RW_i = Relative Weight of the criterion i

W_o = Weight of the objective

A summary of the relative and actual weights can be found in table 2.

5.3.1 Social objectives

5.3.1.1 Resettlement

The recent construction of the Maputo-Katembe bridge in Mozambique has shown that the resettlement of urban population is complex, costly, timely and often socially contested (CLbrief, 2018; Club of Mozambique, 2018).

5.3.1.2Aesthetics

The Masterplan aims to create a *"beautiful Beira",* which means that the aesthetics of the area cannot be neglected. The aesthetics of a city neighbourhood contribute to human well-being and the economic value of the property in the area (Seresinhe, Preis & Moat, 2015).

5.3.1.3 Recreation for the city and in the neighbourhood

Both blue and green spaces can introduce space for recreation in an area which has a positive effect on human health and well-being (Mansor, Said & Mohamad, 2010), as well as increase the economic value of properties.

Space for recreation in the neighbourhood was weighted higher than space for recreation for the city, because it is considered to be contributing positively to the daily experience of the citizens.

5.3.2 Ecological objectives

5.3.2.1 Reduction of heat stress

According to Wei et al. (2017) people are more amicable and stable at a temperature of roughly 22°C. A poll in the US indicated that a majority of the people (71.33%) prefer temperatures in the range of 18.3-26.7°C (City-data, n.d.)

The graph (1) above shows Beira's monthly daily temperature averages over the period 1951-2016, (Hikersbay, n.d.). The green belt (20-25°C) shows the temperature range considered ideal by many people. Eleven months a year, the monthly average daily maximum temperature rises above the green belt, meaning that parts of the day temperatures are considered "too hot to be pleasant". For Beira, controlling heat stress is considered important.

5.3.2.2 Biodiversity

Biodiversity is important for the functioning of ecosystems and their services that exist in green spaces (Gemeente Amsterdam, 2011). Ultimately, biodiversity has an impact on human health and well-being (Biodiversity and human health, 1997; World Health Organization, n.d.). Biodiversity is considered of secondary importance.

5.3.2.3 Greenhouse gasses

Both Reduction of carbon emissions (C) and the Emission of greenhouse gasses (CH4) are weighted as important, because both carbon dioxide and methane are drivers for climate change (Stocker et al., 2013). As a result, it is likely (66-100% probability) that the overall annual rainfall will decrease, and equally likely that the intensity of the short storms will increase (Stocker et al., 2013). Beira is a low lying coastal city, with drainage problems. It is especially vulnerable to increased stormwater volumes and sea level rise. Concern about greenhouse gasses is considered to be "a must" for Beira.

5.3.2.4 Recharge of Groundwater

Water shortage is already a problem in Beira (Sophie, 2016). With a population expected to more than double until 2035, measures will have to be taken in order to minimize the problem. Recharge of groundwater is therefore considered to be of increasing importance.

5.3.2.5 Improve open water quality

In Beira, water from open water bodies is used for personal and recreational use. Beira projects a lagoon city especially designed for ecotourism for which the quality of the open water bodies is important (Kalsbeek, 2015). Open water quality has been attributed a relatively high weight.

5.3.3 Economic objectives

5.3.3.1 Land acquisition costs

Population growth rate and pressure on land are high in Beira (Kalsbeek, 2015). Compared to investment costs, land acquisition costs have a higher weight since they involve monetary costs, as well as put a claim on scarce land resources.

5.3.3.2 Investment costs

Funding is often a limiting and deciding factor when it comes to implementing measures, whether they are private or public. Investment costs have been attributed a relatively high weight within the economic objectives.

5.3.3.3 Maintenance costs

For implemented measures to maintain optimal functioning over the years, funding for maintenance is required. Mozambique has in the past already struggled with acquiring enough funding in other areas such as for road maintenance (Michael, 2006). Maintenance costs have been considered important as investment costs.

5.3.3.4 Water Harvesting

Beira already has a water shortage problem. With the projected population growth this problem becomes more urgent to address. Rainwater harvesting and reuse will not only address the shortage, but also change the attitude towards water use. Rainwater harvesting is considered important.

5.3.3.5 Tourism

The *Greeninfra 4 Beira* plan foresees in a lagoon with the potential to develop tourism and generate income for both, the city and its inhabitants, by attracting investors, promoting aquatic activities, and creating jobs (Kalsbeek, 2015). Income from tourism could contribute to fund maintenance costs of the infrastructure. Therefore tourism is considered important.

Objective	Relative Weight	Actual Weight	
Ecological objectives	**170.00**	**33.33**	
Reduction of heat stress	30.00	5.88	Tropical city
Increase biodiversity	20.00	3.92	Functioning of green spaces
Reduction of greenhouse gas (C)	30.00	5.88	Climate change translates to more extreme weather
Emission greenhouse gas (CH4)	30.00	5.88	Climate change translates to more extreme weather
Recharge groundwater	30.00	5.88	Combat water shortage
Improve open water quality	30.00	5.88	Important for tourism
Economic objectives	**180.00**	**33.33**	
Land acquisition costs	50.00	9.26	Needs funding & costs land
Investment costs	40.00	7.41	Needs funding
Maintenance costs	30.00	5.56	Needs funding
Water harvesting	30.00	5.56	Water harvesting needs to be stimulated
Tourism	30.00	5.56	Income generating for the city & inhabitants
Social objectives	**110.00**	**33.33**	
Resettlement	30.00	9.09	Costly, timely and often socially contested
Aesthetics	30.00	9.09	Contributes to the well-being and one of the main goals of the masterplan
Recreational space for the city	20.00	6.06	Contributes to the well-being
Recreational space in the neighbourhood	30.00	9.09	Neighborhood spaces are valued higher than city spaces

Table 2: : Summary of the relative and actual weights

5.4 Ranking

The weighted summation formula has been applied to determine the ranking of each of the alternatives. The formula is relatively simple to use and explain, and therefore a useful tool in decision making (van Herwijnen & Janssen, 2004). For each alternative $(\boldsymbol{a_j})$, the standardized score per criterion $(\widehat{\boldsymbol{s_{ij}}})$ is multiplied by the attributed weight and summed together as in equation 4.

$$score\ (a_j) = \sum_{i=1}^{N} W_i \times \widehat{s_{ij}} \qquad (4)$$

Where:

a_j= the alternative j

N = number of criteria

w_i= the weight of criterion i

$\widehat{s_{ij}}$= standardized score of alternative j on criterion i.

The ranking of an alternative can change or remain the same when different weights are applied, giving a good insight in the relative overall value of the alternative.

6 Results

Before discussing the results, it must be emphasized that the attributed scores depend on the final design of measures in mind. A retention basin built for the sole purpose of flood mitigation will not score on aesthetics, biodiversity and recreational space, while a retention basin designed to serve all objectives naturally will score on all these criteria. In the MCA the scores are attributed with a certain final design in mind, as described in the Chapter Description of the Alternatives.

Another relevant observation is that *implementation time*, at first considered an important criteria, was left out of the MCA since it was impossible to come up with a relevant scoring method. A flat roof can be converted into a blue roof in days, while the construction of a lagoon takes years. However, in order to create the same amount of storage on blue roofs as in a single lagoon can take years and requires sufficient square meters of suitable rooftops available.

6.1 Score table

On the next two pages the score table per alternative and per criterion is provided. References can be found in the Annex.

MCA Results per m³ storage created
Even weights

Objective	C/B	Unit	Actual Weight	private roofs Blue roofs	private roofs Private intensive green roofs	private roofs Public intensive green roofs	private roofs Extensive green roofs	private roofs Blue-green roof	private Rainwater harvesting Standard RWH dam	private Rainwater harvesting RRWH + under-ground storage	private Rainwater harvesting RRWH + above-ground storage
Ecological objectives			**33.33**								
Reduction of heat stress	B	points	5.88	0	65.36	65.36	43.57	32.68	0	0	0
Increase biodiversity	B	0-2	3.92	0	2	2	2	2	1	1	1
Reduction of Greenhouse gas (C)	B	g/yr	5.88	0	6127.45	6127.45	8169.93	6127.45	0	0	0
Emission Greenhouse gas (CH4)	C	g/yr	5.88	0	10.31	10.31	13.74	10.31	0	0	0
Recharge groundwater	B	m^3/hr	5.88	0	0	0	0	0	0	0	0
Improve open water quality	B	points	5.88	1.5	2.5	2.5	2.5	2.5	1.5	1.5	1.5
Economic objectives			**33.33**								
Land acquisition costs	C	€	9.26	0	0	0	0	0	0	0	0
Investment costs	C	1-18	7.41	12	17	17	16	15	10	13	11
Maintenance costs	C	1-18	5.56	13	16	16	18	15	10	14	11
Water harvesting	B	m^3	5.56	0	0	0	0	0	1	1	1
Tourism	B	0-1	5.56	0	0	0	0	0	0	0	0
Social objectives			**33.33**								
Resettlement	C	0-2	9.09	0	0	0	0	0	0	0	0
Aesthetics	B	0-2	9.09	1	1	2	1	1	1	1	1
Recreation for the city	B	0-1	6.06	0	0	1	0	0	0	0	0
Recreation in the neighbourhood	B	0-1	9.09	0	0	0	0	0	0	0	0

Table 3: MCA results of the private alternatives per m³ storage created, based on even weights per objective

MCA Results per m³ storage created

Even weights

Objective	C/B	Unit	Actual Weight	public Infiltration **Permeable pavements**	public Infiltration **Engi-neered swales**	public Infiltration **Native soil swales**	public Retention **Bare soil multi-use detention area**	public Retention **Green multi-use detention area**	public Retention **Dry detention pond**	public Retention **Wet retention pond**	public Retention **Retention basin**	public Retention **Wetland**	public Retention **Lagoon**
Ecological objectives			**33.33**										
Reduction of heat stress	B	points	5.88	0	1.66	2.76	0	4	1	0.71	0	4	0.71
Increase biodiversity	B	0-2	3.92	0	2	2	1	2	1	2	1	2	2
Reduction of Greenhouse gas (C)	B	g/yr	5.88	0	311.2	517.24	0	375	187.5	0	0	960	37.14
Emission Greenhouse gas (CH4)	C	g/yr	5.88	0	0.52	0.87	0	0.63	0.32	32.59	0	72.86	32.59
Recharge groundwater	B	m^3/hr	5.88	3694.48	348.55	274.76	199.2	199.2	99.6	0.07	0	0.19	0.07
Improve open water quality	B	points	5.88	4	4	4	4.5	4.5	4.5	1.5	2	1.5	2
Economic objectives			**33.33**										
Land acquisition costs	C	€	9.26	0	36.78	61.13	0	0	22.16	15.83	7.39	44.32	15.83
Investment costs	C	1-18	7.41	14	9	8	1	5	3	3	5	7	2
Maintenance costs	C	1-18	5.56	9	6	4	1	7	1	8	5	1	12
Water harvesting	B	m^3	5.56	0	0	0	0	0	0	0	1	0	0
Tourism	B	0-1	5.56	0	0	0	0	0	0	0	0	1	1
Social objectives			**33.33**										
Resettlement	C	0-2	9.09	0	0	0	1	1	1	1	2	2	2
Aesthetics	B	0-2	9.09	1	2	2	1	2	2	2	1	2	2
Recreation for the city	B	0-1	6.06	0	0	0	0	1	0	0	0	1	1
Recreation in the neighbourhood	B	0-1	9.09	0	0	0	1	1	1	1	0	0	0

Table 4 MCA results of the public alternatives per m³ storage created, based on even weights per objective:

	Blue roofs	Private intensive green roofs	Public intensive green roofs	Extensive green roofs	Blue-green roof	Standard RWH dam	RRWH + under-ground storage	RRWH + above-ground storage
Ecological objectives	5.88	21.22	21.22	20.46	18.28	7.84	7.84	7.84
Economic objectives	13.21	9.91	9.91	9.72	11.16	20.67	17.97	19.88
Social objectives	9.09	9.09	24.24	9.09	9.09	9.09	9.09	9.09
Total score	28.18	40.23	55.38	39.27	38.54	37.6	34.9	36.81

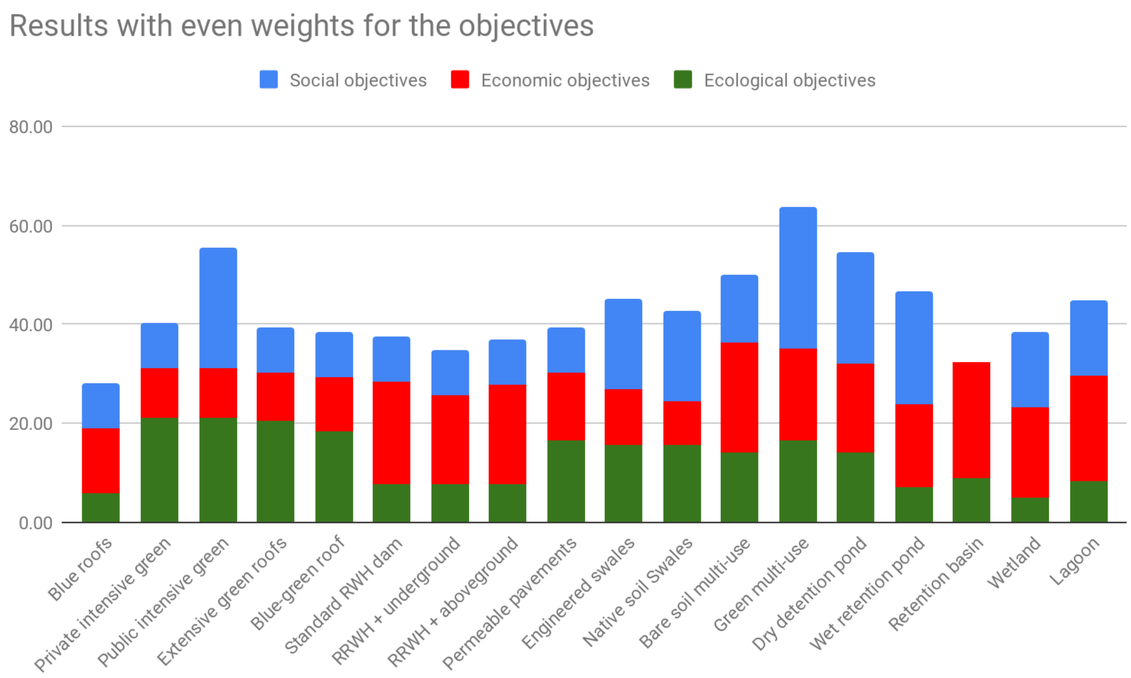
Table 5: Scores per objective of the private alternatives

	Permeable pavements	Engi-neered swales	Native soil swales	Bare soil multi-use detention area	Green multi-use detention area	Dry detention pond	Wet retention pond	Retention basin	Wetland	Lagoon
Ecological objectives	16.67	15.59	15.69	14.04	16.58	14.08	7.24	8.82	4.97	8.24
Economic objectives	13.59	11.31	8.74	22.22	18.41	17.94	16.61	23.5	18.29	21.32
Social objectives	9.09	18.18	18.18	13.64	28.79	22.73	22.73	0	15.15	15.15
Total score	39.34	45.08	42.61	49.9	63.77	54.75	46.57	32.32	38.41	44.71

Table 6: Scores per objective of the public alternatives

6.2 Even weights for the three objectives

For the initial results analysis, the weights for the different objectives, social, economic and ecological, are set to 33.33% for each of the objectives. The MCA results show that, based on the three dimensions of sustainability (people, planet, profit), the green multi-use detention area has the highest cumulative score, closely followed by the public green roof and the dry detention pond. The alternatives with the lowest cumulative scores on the three dimensions of sustainability are the blue roofs, followed by the retention basin (graph 2).



Graph 1

On the *Social objectives*, the green multi-use detention area and public intensive green roof score the highest, while the retention basin scores the absolute lowest. The public intensive green roof scores particularly high due to the absence of the need to resettle people, the increase in aesthetic value, and the creation of recreational space for the city. But this comes at a high cost, since the alternative scores among the worst in economic objectives. Retention basins on the other hand do not contribute to the aesthetics of the area nor recreational space and demand people to resettle and as a result do not score any points for social objectives.

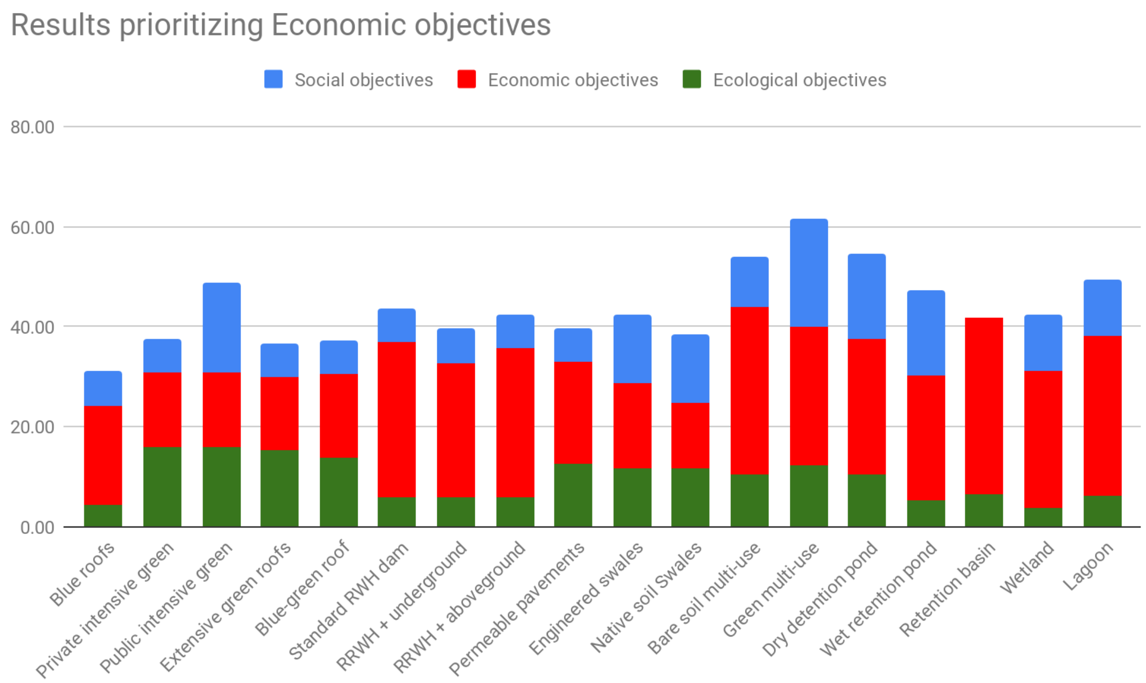
Private and public intensive green roofs have the highest score when it comes to *Ecological objectives* due to their low storage capacity per square meter and therefore large area needed to supply 1m^3 of storage. Surprisingly Wetlands score the worst on ecological objectives due to the relatively low reduction of heat stress within the city and relatively high CH_4 emission rates, poor recharge of groundwater and low effect on the improvement of water quality. The rainwater harvesting measures and blue roof score relatively low due to the inability to reduce heat stress, increase biodiversity, reduce greenhouse gases and recharge groundwater.

Looking at the *Economical objectives*, the retention basin has the highest score. What makes the retention basin appealing is the relatively low land, investment and maintenance costs per m^3 storage as well as the potential to harvest rainwater. Native soil swales score the lowest for the economical objectives mainly due to the relatively high land acquisition and investment costs, inability to harvest rainwater and no potential for tourism.

6.3 Sensitivity analysis

6.3.1 Prioritizing Economic objectives

Economics is often the deciding factor in choosing an alternative, especially in low to medium income countries, therefore the weight applied to Economics is taken as the sum of the Social and Ecological Objectives, 50, 25 and 25 respectively. The results can be seen in the graph below.



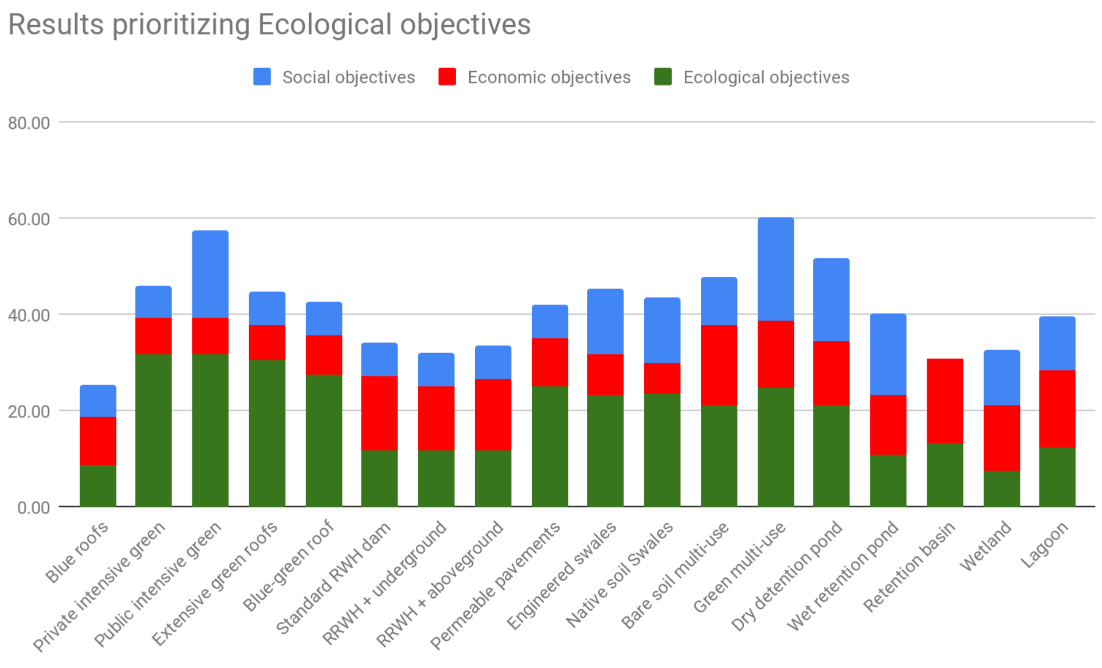
Graph 2

The Green multi-use retention area continues to score the highest, followed closely by the dry detention pond, the bare soil multi-use retention area and the lagoon, meaning they are all cost-effective alternatives with good scores on the other objectives. Despite being highly costly, the public intensive green roof continues to score high, this is mainly due to the fact that the investment criteria is scored as a "ordinal scale" instead of as a maximum. By scoring the investment criteria on a maximum scale, the differences between the alternatives with low investment costs would become too compressed.

Interestingly the rainwater harvesting solution have become more attractive. The blue roof remains the alternative with the lowest score, despite scoring quite high on economic objectives.

6.3.2 Prioritizing Ecological objectives

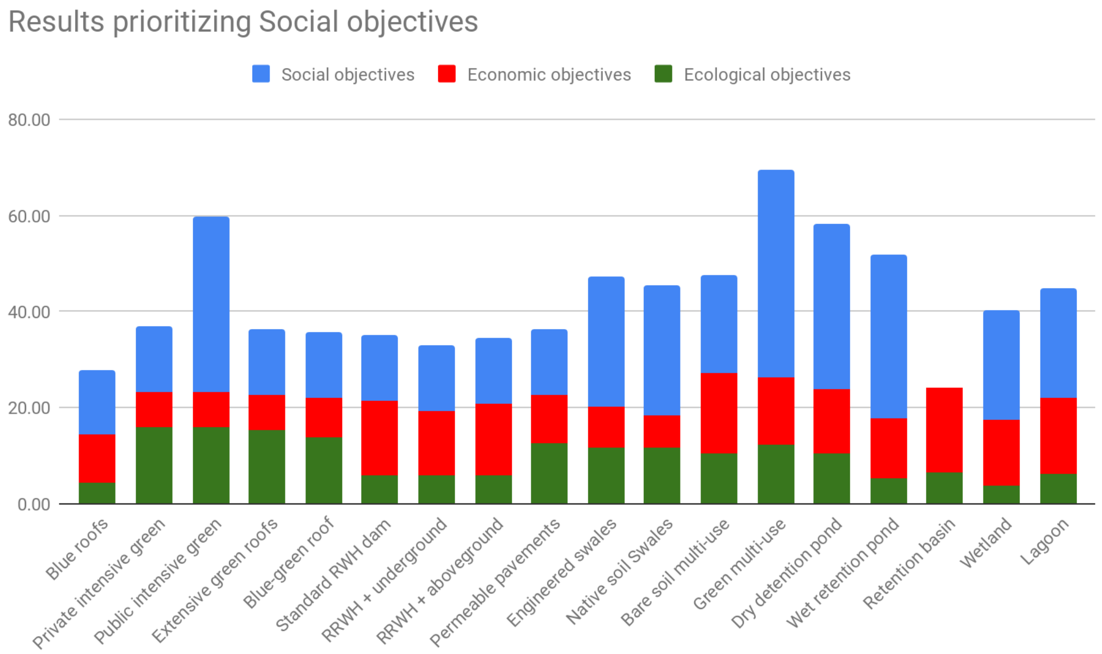
When ecological objectives are prioritized and the weights of the social, economic, and ecological objectives are changed to 25, 25, 50% respectively, the green alternatives do better (graph 4). The overall pattern remains more or less the same. Remarkable is that wetlands and lagoons, in contrast to popular belief do not score high on the ecological objective. This is mainly due to the fact that whilst they do contribute to biodiversity they score poor on the decrease of heat stress, carbon sequestration, methane emissions, the recharge of groundwater and improving water quality.



Graph 3

6.3.3 Prioritizing Social objectives

Prioritizing Social Objectives, the weights are changed to 50, 25, and 25% for Social, Economic and Ecological objectives respectively.



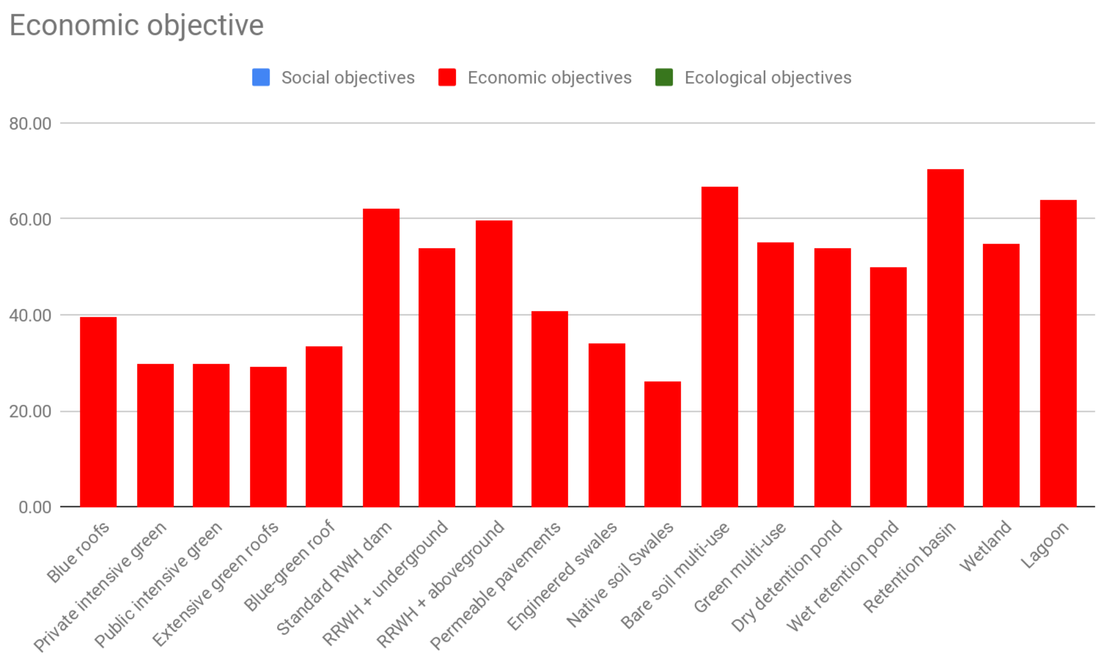
Graph 4

The green multi-use retention area continues to be the best alternative, with the public intensive green roof becoming the second best alternative. The worst two alternatives are the blue roof and the retention basin. Not surprisingly all on-plot alternatives score relatively low when social aspects come into play.

6.3.4 Single objective analysis

A multi-criteria analysis allows for testing extreme choices. Since financial and economic arguments tend to be important, the weights of the Social, Ecological and Economic objectives were changed to 0, 0, and 100% respectively. The results are shown in the graph below.

The retention basin scores highest, followed by the bare soil multi-use retention area. Interestingly the rainwater harvesting alternatives on private soil have become competitive.



Graph 5

It must be noted that on-plot, close to the source, rainwater harvesting alternatives scored low in the former analysis, but here show to be a cost-effective way of creating flood storage. This is due to the fact that these alternatives have little to no ecological benefits and only have limited social benefits (no resettlement needed). Even the blue roof has become more interesting as an alternative.

6.4 Ranking of the alternatives

Table 7 below summarizes the rankings of the SuDS alternatives in the different MCA scenarios.

It is interesting to see that in a multi criteria analysis the green multi-use detention area scores best in all scenarios, except for the pure economic objective scenario, where it still scores reasonable. The retention basin scores among the worst in all scenarios, except for the pure economic evaluation. This explains why "water engineers" come up frequently with this solution.

The private on-plot rainwater harvesting alternatives score low when analysed in this multi-criteria analysis, but do score well economically. They are the most economically feasible options for private plot owners.

Ranking of Alternatives		Even weights	Priori. econ. object.	Prior. ecol. object.	Prior. soc. object.	Single econ. object.
Public/ Private Invest.	Ecological Economic Social	33.33 33.33 33.33	25 50 25	50 25 25	25 25 50	0 100 0
Private	Blue roofs	18	18	18	17	12
Private	Private intensive green roofs	9	15	5	10	15
Private	Public intensive green roofs	2	5	2	2	15
Private	Extensive green roofs	11	17	7	12	17
Private	Blue-green roof	12	16	9	13	14
Private	Standard RWH dam	14	7	13	14	4
Private	RRWH + underground storage	16	13	16	16	8
Private	RRWH + aboveground storage	15	9	14	15	5
Private	Permeable pavements	10	12	10	11	11
Public	Engineered swales	6	10	6	6	13
Public	Native soil swales	8	14	8	7	18
Public	Bare soil multi-use detention area	4	3	4	5	2
Public	Green multi-use detention area	1	1	1	1	6
Public	Dry detention pond	3	2	3	3	9
Public	Wet retention pond	5	6	11	4	10
Public	Retention basin	17	11	17	18	1
Public	Wetland	13	8	15	9	7

Legend	
(dark red)	Worst alternative
(light red)	Second worst alternative
(dark green)	Best alternative
(light green)	Second best alternative
(orange)	Best alternatives for private plot owners

Table 7:Ranking of the SuDS alternatives under different prioritization scenarios

7 Evaluation of the plans

Over the past 5 years, at least three plans have been developed as a solution for the flooding events in Beira: the Beira Masterplan, developed in 2013 (BMP 2013); the Greeninfra 4 Beira plan, developed in 2015 (GI4B); and the Capacity Development Programme, developed in 2017, (CDP). Table 8 below summarizes the alternatives proposed in the developed plans.

Note:

A complete list of the alternatives proposed by the Greeninfra 4 Beira plan is not available. In the table below the alternatives mentioned in the plan are indicated.

Ranking of Alternatives		Even weights	Priori. econ. object.	Prior. ecol. object.	Prior. soc. object.	Single econ. object.	**Plans**		
Public/ Private Invest.	Ecological Economic Social	33.33 33.33 33.33	25 50 25	50 25 25	25 25 50	0 100 0	BMP 2013	GI4B 2015	CDP 2017
Private	Blue roofs	18	18	18	17	12			
Private	Private intensive green roofs	9	15	5	10	15			
Private	Public intensive green roofs	2	5	2	2	15			
Private	Extensive green roofs	11	17	7	12	17			
Private	Blue-green roof	12	16	9	13	14			
Private	Standard RWH dam	14	7	13	14	4			
Private	RRWH + underground storage	16	13	16	16	8			
Private	RRWH + aboveground storage	15	9	14	15	5			
Private	Permeable pavements	10	12	10	11	11			
Public	Engineered swales	6	10	6	6	13			
Public	Native soil swales	8	14	8	7	18			
Public	Bare soil multi-use detention area	4	3	4	5	2		X	
Public	Green multi-use detention area	1	1	1	1	6			
Public	Dry detention pond	3	2	3	3	9			
Public	Wet retention pond	5	6	11	4	10			
Public	Retention basin	17	11	17	18	1	X	X	X
Public	Wetland	13	8	15	9	7		X	
Public	Lagoon	7	4	12	8	3		X	

Table 8: Ranking of the alternatives vs. Alternatives used in developed plans

The first conclusion is that all plans have considered flood mitigation as a public responsibility, to be solved solely by the public entities in the public space, this despite the fact that the problem is caused by multiple private investments, and the fact that relatively low cost on-plot alternatives are available. Measures at the source, that share the financial burden between public and the private investors are not considered. Especially for the new to build areas, these measures often reduce further in costs and could be imposed by building regulations.

The common measure across all plans, *the retention basin*, does not score high on the "liveable city concept", but seems to be the favorite among planners due to its economic benefits. Low cost "single objective" alternatives might seem cost effective when it comes to flood mitigation, but it requires additional space and investment to address other aspects to create the desired "liveable city".

An interesting opportunity arises looking at the multi-use detention areas. The relatively cheap bare soil multi-use detention area, can overtime be transformed into a green multi-use detention area, building gradually towards a more livable city while spreading the investment costs.

The same opportunity, although less attractive from a hydraulic and economic point of view, exists for the roofs. Blue roofs are relatively cheap in comparison to the green roofs. In a first phase, blue roofs could be installed on existing and new buildings. At a later stage, blue roofs could be turned into green roofs.

Compared to other alternatives, green roofs are an extremely expensive way to create storm water storage. While they do have a beneficial effect in reducing run-off in minor storms, their limited storage capacity per square meter makes their effect on run-off in heavy tropical rainstorms minor. This was also found in a hydraulic simulation in Batam by Busker (2015).

The Green Infrastructure for Beira plan (2015) proposes to invest in a lagoon that could attract tourism and to create a lagoon city. The lagoon scores among the best on the economic objectives. The plan foresees in selling one hundred surrounding plots at a price of USD 7,500 each. This would not cover the costs of constructing the lagoon and could be seen as "sponsoring the elite", as the plot price is low in comparison to the value of the houses to be built in the lagoon city. Selling the plots at a market price, could probably fund the lagoon alternative.

8 Conclusions & Recommendations

The Multicriteria Analysis is a useful tool that can help with the design and evaluation of flood mitigation strategies and plans and the decision making process. The MCA creates insights that can confirm choices made, detect opportunities left out, and develop strategies over time.

The Multicriteria Analysis tool should be used creatively, as it has the ability to analyse extremes, such as excluding one or two objectives from the equation, to get specific insights, as shown in the single economic objective analysis.

Few data were available for the specific situation of Mozambique and Beira, and the performance of alternatives in a tropical climate. Although the tool still was able to show interesting insights, it is recommended that more local research is done to gather relevant data and even better insights.

9 Annex

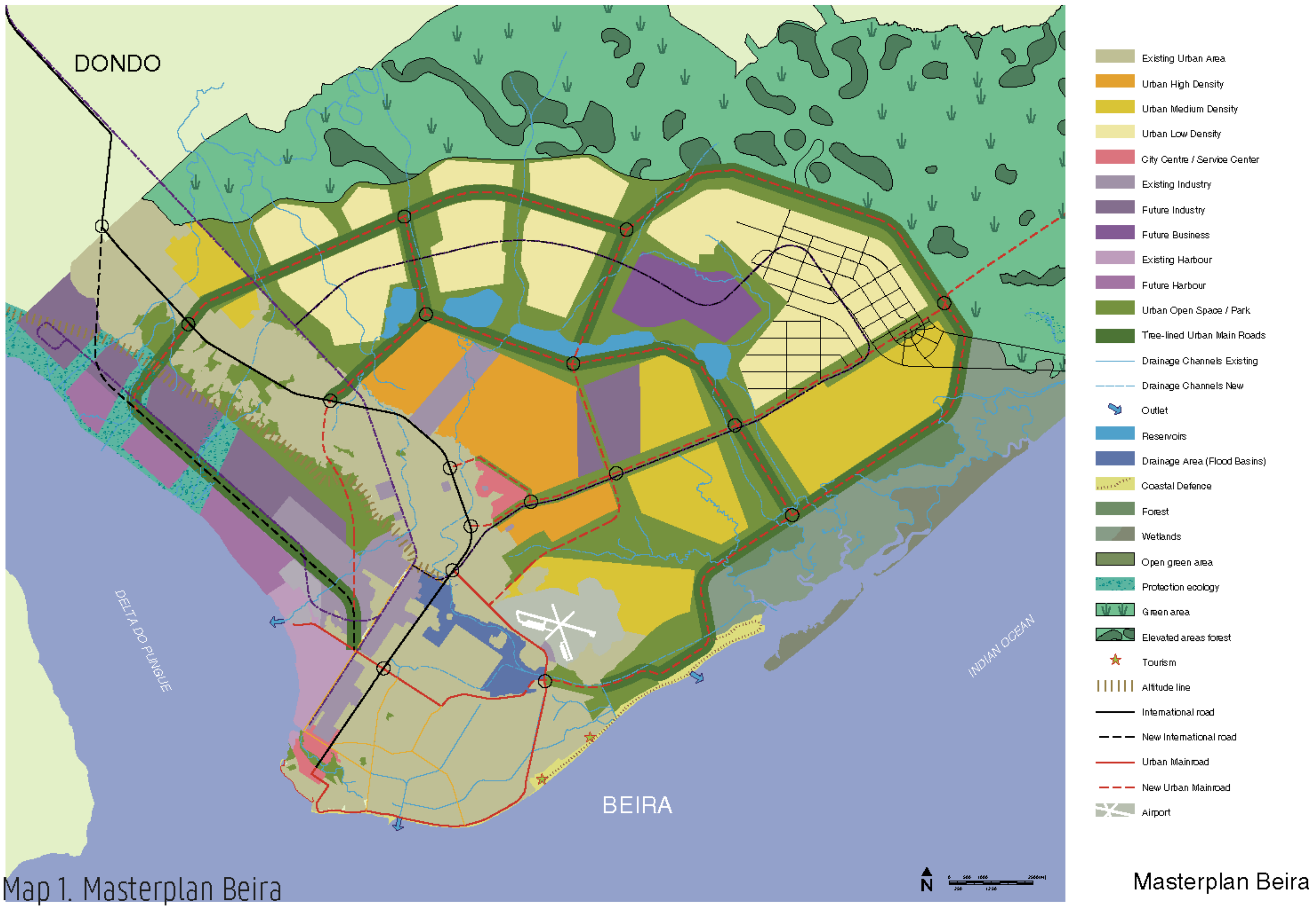


Figure 18: Beira Masterplan, See Annex for legend (van Weelden, 2013)

References Private Alternatvies

Objective	Blue roofs	Private intensive green roofs	Public intensive green roofs	Extensive green roofs	Blue-green roof	Standard RWH dam	RRWH + under-ground storage	RRWH + above-ground storage
Ecological objectives								
Reduction of heat stress	-	11, 15, 26	11, 15, 26	11, 15, 26	11, 15, 26	-	-	-
Increase biodiversity	-	16	16	16	16	-	-	-
Reduction of Greenhouse gas (C)	-	9	9	9	9	-	-	-
Emission Greenhouse gas (CH4)	-	21	21	21	21	-	-	-
Recharge groundwater	-	-	-	-	-	-	-	-
Improve open water quality	-	-	-	-	-	-	-	-
Economic objectives								
Land acquisition costs	-	-	-	-	-	-	-	-
Investment costs	8	17	17	17	35	13	4	5
Maintenance costs	28	17	17	17	34	28	28	28
Water harvesting	-	-	-	-	-	13	4	5
Tourism	-	-	-	-	-	-	-	-
Social objectives								
Resettlement	-	-	-	-	-	-	-	-
Aesthetics	-	20	20	20	20	-	-	-
Recreation for the city	-	-	-	-	-	-	-	-
Recreation in the neighbourhood	-	-	-	-	-	-	-	-

Table 9: References of the private alternatives

References Public alternatives

Objective	public Infiltration **Permeable pavements**	public Infiltration **Engi-neered swales**	public Infiltration **Native soil swales**	public Retention **Bare soil multi-use detention area**	public Retention **Green multi-use detention area**	public Retention **Dry detention pond**	public Retention **Wet retention pond**	public Retention **Retention basin**	public Retention **Wetland**	public Retention **Lagoon**
Ecological objectives										
Reduction of heat stress	-	19	19	-	31	32	10	-	10	10
Increase biodiversity	-	19	19	-	31	32	24	-	2	14
Reduction of Greenhouse gas (C)	-	9	9	-	9	9	29	-	22	3
Emission Greenhouse gas (CH4)	-	21	21	-	21	21	7	-	7	7
Recharge groundwater	27	27	27	27	27	27	30	-	23	30
Improve open water quality	-	-	-	-	-	-	-	-	-	-
Economic objectives										
Land acquisition costs	-	1	1	-	-	1	1	1	1	1
Investment costs	12	33	12	12	12	12	12	12	12	14
Maintenance costs	12	33	12	12	12	12	12	12	12	14
Water harvesting	-	-	-	-	-	-	-	-	-	-
Tourism	-	-	-	-	-	-	-	-	14	14
Social objectives										
Resettlement	-	-	-	-	-	-	-	6	-	-
Aesthetics	-	18	18	-	20	20	24	-	25	14
Recreation for the city	-	-	-	-	-	-	-	-	14	14
Recreation in the neighbourhood	-	-	-	-	-	-	-	-	-	-

Table 10: References of the Public alternatives

#	Publication
1	(Anonymous, 2018)
2	(Bacon, 1997; Junk et al., 2014)
3	(Brevik & Homburg, 2004)
4	(Builders, n.d. 1)
5	(Builders, n.d. 2)
6	(Deltares., n.d.).
7	(Devol et al., 1990)
8	(Foster et al., 2011)
9	(Getter, Rowe, Robertson, Cregg & Andresen, 2009)
10	(Gunawardena, Wells & Kershaw, 2017)
11	(Hien, Yok & Yu, 2007)
12	(HR Wallingford, 2004)
13	(Kahinda et al., 2007)
14	(Kalsbeek, 2015)
15	(Mentens, Raes & Hermy, 2006)
16	(Oberndorfer et al., 2007)
17	(Peck & Kuhn, n.d.)
18	(Pille & Saeumel, 2016)
19	(Polypipe. n.d.)
20	(Rozos, Makropoulos & Maksimović, 2013)
21	(Sanhueza & Donoso, 2006)
22	(Saunders, Jones & Kansiime, 2007)
23	(Sun, Saeed & Zhang, 2013)
24	(Susdrain, n.d.2)
25	(Susdrain, n.d.3)
26	(Takebayashi, Moriyama, 2007)
27	(Valinski & Chandler, 2015)
28	2% rule applied
29	Assumed same as lagoon, (Brevik & Homburg, 2004)
30	Assumed same as wetland, (Sun, Saeed & Zhang, 2013)
31	Assumed same principle as with intensive green roofs, (Hien, Yok & Yu, 2007)
32	Assumed same principle as with native soil swales and green roofs (Hien, Yok & Yu, 2007)
33	Assumed to be 2*native soil swale. (HR Wallingford, 2004)
34	Assumed to be equal to extensive green roof. (Peck & Kuhn, n.d)
35	Assumed to be same as extensive, what is saved on extensive is used for blue roof. (Peck & Kuhn, n.d.)

Table 11: References and assumptions

	Blue roofs	Private intensive green roofs	Public intensive green roofs	Extensive green roofs	Blue-green roof	Standard RWH dam	RRWH + under-ground storage	RRWH + above-ground storage
Surface area (m^2)	-	-	-	-	-	0.5	0.5	0.5
Roof area (m^2)	6.67	32.68	32.68	43.57	32.68	-	-	-
Source	9, 11	3, 7, 13	3, 7, 13	3, 7, 13	3, 7, 11, 13	5	1	2

Table 12: Area and references of private alternatives

	Permeable pavements	Engi-neered swales	Native soil swales	Bare soil multi-use detention area	Green multi-use detention area	Dry detention pond	Wet retention pond	Retention basin	Wetland	Lagoon
Surface Area (m^2)	23.5	1.66	2.76	2	2	1	0.71	0.33	2	0.71
Source	8	10	18	15	15	16	17	4	14	6

Table 13: Area and references of public alternatives

#	Publication	#	Publication
1	(Builders, n.d. 1)	10	(Rioned, n.d.)
2	(Builders, n.d. 2)	11	(Roy, Quigley & Raymond, 2014)
3	(Chow & Bakar, 2016; Speak, et al., 2013)	12	(Simon, 2015)
4	(Consultancy services for the capacity development programme under the climate change adaptation component, 2018)	13	(Speak et al., 2013)
5	(Department of water affairs and forestry, 2007)	14	(Sun, Saeed & Zhang, 2013)
6	(Kalsbeek, 2015)	15	Depth assumed equal to that of the Wetland
7	(Nagase & Dunnett, 2012)	16	Depth assumed from the maximum groundwater level rise (Simon, 2015)
8	(Park, Sandoval, Lin, Kim & Cho, 2014)	17	Depth assumed to be the same as Lagoon (Kalsbeek, 2015)
9	(PWD, n.d)	18	Shallower to compensate for permeability and soil characteristics

Table 14: References and assumptions for the surface/roof area needed

10 References

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