Back to Mother Nature

The potential of using nature-based solutions to mitigate climate change vulnerabilities along the coast of Dar es Salaam, Tanzania.

Julian Cortes

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LUCSUS
Lund University Centre for Sustainability Studies

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Abstract

Climate change has been identified as one of the greatest threats facing our world today. The effects of climate change are expected to increase global sea level rise and the frequency and intensity of extreme weather events. This poses a significant risk to cities due to their high population density and economic, political, cultural and commercial activities. Coastal cities in low- and middle-income countries are most at risk due to their low adaptive capacity. Global assessments have identified East Africa as one of the most threatened coastal regions. This is because East African cities are undergoing substantial unplanned growth, which increases the exposure of people and assets to climate change impacts. Little research has been conducted on potential adaptation measures to climate change in this region. This thesis assesses the potential for nature-based solutions to be used to mitigate climate change vulnerabilities along the coast of Dar es Salaam, where grey infrastructure solutions have traditionally been used. Both quantitative and qualitative methods are used to do so. Key informant interviews combined with a geospatial analysis was used to identify vulnerabilities to climate change and locate suitable areas for different nature-based solutions. The results showed that there were suitable areas for nature-based solutions to address adaptation gaps in coastal Dar es Salaam. Mangroves, coral reefs, seagrass and sand dunes were found to be viable options along the coast of Dar es Salaam. This thesis concludes that the use of nature-based solutions can offer relatively inexpensive, effective and long-lasting climate change adaptation solutions that create a range of co-benefits both for coastal ecosystems and for the economic lives of local communities in and around Dar es Salaam's coastal region. This thesis provides a scientific basis to support evidence-based policy making on sustainable adaptive management in Tanzania, with potential applications in other coastal urban areas in sub-Saharan Africa and other developing countries.

Keywords: climate change, nature-based solutions, suitability analysis, coastal vulnerability, Dar es Salaam, adaptation

Word count: 11,804

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1. Introduction

Climate change has been identified as one of the greatest threats facing the world today (Awuor, Orindi & Adwera, 2018). Globally, the effects of climate change are expected to intensify a range of climatic aspects, including accelerating global sea-level rise (Almeida Martins & Costa Ferreira, 2011). According to the Intergovernmental Panel on Climate Change (IPCC), the frequency, intensity, spatial extent and duration of extreme weather events are also expected to change (IPCC, 2014). Climate change poses a significant threat to human populations as it can negatively impact agricultural production, water resources and socio-economic development (Luhunga et al., 2018). Cities are particularly vulnerable to the effects of climate change due to their high population density and because they are key centres of economic, political, cultural, social and commercial activities (Awuor, Orindi & Adwera, 2018; Depietri & McPhearson, 2017). Although cities only cover about 3% of the Earth's surface, they are home to over 55% of the world's population. This number is expected to increase to 68% by 2050 (Liu et al., 2014; UN, 2018).

Many cities are located along coastal areas, making them especially vulnerable to climate change-related events because they are naturally exposed to changing sea-levels, storms and extreme weather events. (McGranahan et al., 2007; Almeida-Martins & Costa-Ferreira, 2011; EC, 2015; START, 2011; Kebede & Nicholls, 2011). These risks are expected to be exacerbated by climate change (IPCC, 2014). More frequent windstorms and higher rainfall can create tidal surges and floods that heavily impact people's livelihoods and infrastructure (START, 2011). Increased sea-level rise would also result in stronger storm surges and flooding, which would lead to more extensive encroachment of salt-water, loss of wetlands and increased rates of erosion (START, 2011; Kebede & Nicholls, 2011). As a result, climate change poses serious risks to the population, habitats and natural resources of coastal areas (Almeida Martins & Costa Ferreira, 2011).

Coastal cities, especially in lower- and middle-income countries are most at risk from the impacts of climate change due to their low adaptive capacity resulting from limited financial, technological and institutional capacity (Awuor, Orindi & Adwera, 2018). Inhabitants of coastal areas in lower- and middle-income countries are disproportionately vulnerable to the effects of climate change due to their reliance on natural coastal infrastructure, which provide ecosystem services such as food production, water treatment and income generation (RF, 2013). Generally speaking, lower-income communities live in marginalised lands and face greater risks due to their limited capacity to respond, stemming from less access to resources, information and safety nets (START, 2011). In addition to climate change, urbanisation creates pressures on ecosystems such as loss and degradation of natural areas, soil sealing and densification, which all inhibit ecosystem functioning (Kabisch, 2016). Few, if any coastal cities in the developing world are prepared for the impacts of today's and future extreme weather events, let alone climate change and associated sea-level rise (Kebede & Nicholls, 2011; Nicholls et al., 2008; McGranahan et al., 2007).

Growing coastal cities such as Dar es Salaam, in Tanzania, are especially in need of appropriate management responses to climate change (START, 2011). Dar es Salaam is Tanzania's largest coastal city and the country's former capital (Kiunsi, 2013; Todd et al., 2019). Dar es Salaam is exposed to sea-level rise, floods, coastal erosion, droughts, heat waves and is highly vulnerable to these impacts due to ineffective urban planning (START, 2011). About 80% of settlements in the city are unplanned, characterised by high poverty rates and lack of basic infrastructure (Kiunsi, 2013). Climate change in Dar es Salaam can increase hazard-exposure along with the ecological pressures the city is already facing (Todd et al., 2019). The coastal zones of the city contain high population densities, important ecosystem services and significant economic activities (Kebede & Nicholls, 2011). Little research has been conducted on the impacts of climate change on Dar es Salaam and potential adaptations (Maliondo, Mpeta & Olson; 2012).

Recently however, there has been growing recognition that nature-based solutions have the potential to counter such pressures (Stein et al., 2013; Jones et al., 2012). Nature-based solutions are actions that are inspired by nature and can not only improve or restore biodiversity but also help in adapting to climate change (Stein et al., 2013; Jones et al., 2012). A specific type of nature-based solution, known as ecosystem-based adaptation are measures that use biodiversity and ecosystem services to help people and areas adapt to the effects of climate change (CBD, 2009). Careful implementation of such nature-based solutions has tremendous potential for reducing climate change-related vulnerabilities in an energy, resource and cost-efficient manner (EC, 2015). When adapted to local conditions, nature-based solutions have shown to be a promising adaptation strategy that successfully creates multiple social, economic and cultural co-benefits for local communities (EC, 2015; CBD, 2009).

The purpose of this paper is to investigate the potential for using nature-based solutions in Dar es Salaam, Tanzania, as a form of climate change adaptation. To guide this investigation, this thesis asks the following questions:

1. To what extent are coastal areas of Dar es Salaam exposed to climate change vulnerabilities?

2. To what extent can nature-based solutions be used to mitigate vulnerabilities to climate change in coastal areas of Dar es Salaam?

3. Where are potential areas for the implementation of the most suitable nature-based solution along the coast of Dar es Salaam?

2. Background / Literature Review

2.1 Nature-based Solutions

Nature-based (or 'green') solutions (NbS) are increasingly being recognised as having the potential to not only protect biodiversity and safeguard ecosystem services, but also help adapt to climate change (Seddon, 2018). Ecosystem-based Adaptation (EbA) measures are nature-based solutions specifically targeted at helping people adapt to the impacts and hazards of climate change (Seddon, 2018). The term was first coined by the Convention on Biological Diversity (CBD), which defined it as "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change" (CBD, 2009, p.41).

Studies have shown that the use of nature-based solutions not only benefit human and ecological systems, but also have significant economic benefits (Seddon, 2018). In the United States, coastal wetlands were estimated to protect US$625 million worth of infrastructure from direct flood damages during Hurricane Sandy in 2012 (Narayan et al., 2017). The wetlands were estimated to reduce damage by 20-30% in over half the affected areas (Narayan et al., 2017). The areas with the most intact wetlands provided the greatest extent of protection to nearby infrastructure. A global valuation study showed that without coral reefs, annual expected damages from flooding would double and costs from storm events would triple (Seddon, 2018).

In addition to economic benefits, nature-based solutions also provide a range of co-benefits (Seddon, 2018). Nature-based solutions enhance ecosystem services and provide access to food and water, pollination, soil fermentation, carbon storage and habitat provisioning for increased biodiversity (Daigneault, Brown & Gawith, 2016; Van der Nat et al., 2016; Van Slobbe et al., 2013). A 25-year forest restoration project in the Poyang Lake Basin in Southern China greatly reduced soil erosion, while increasing carbon sequestration five-fold (Huang, Shao & Liu, 2012). The net income of local farmers during this period increased six-fold (Huang, Shao & Liu, 2012). Comparably, afforestation efforts in South Korea significantly reduced disaster risk while at the same time increasing carbon sequestration (Lee et al., 2018). The co-benefits range from providing food and income to local communities to restoring biodiversity within ecosystems. A positive causal loop can be created from the well-managed implementation of nature-based solutions where ecological functioning as well as livelihoods benefit.

Although the number of studies investigating the effectiveness and co-benefits of nature-based solutions is increasing (Kabisch et al., 2017; Bridges et al., 2015; Ferrario et al., 2014; CBD, 2009), there remains a gap in comparisons between nature-based solutions and traditional approaches (Seddon, 2018). A recent study compared the efficacy of nature-based solution such as mangroves, sand dunes, saltmarshes, seagrass, kelp beds and reefs to conventional grey-infrastructure such as seawalls and breakwaters (Morris et al., 2018). The study concluded that grey-infrastructure is both economically and ecologically unsustainable (Morris et al., 2018). Rather, the study recommended using nature-based solutions as a basis for restoring natural habitats. A study by The Royal Society (2014) compared nature-based solutions with hybrid and engineered methods. The study compared their efficiency in reducing the risk people faced from extreme weather events, by comparing effectiveness, which was assessed by the magnitude of the event for which the option was effective against the cost (The Royal Society, 2014). Nature-based solutions and hybrid measures (a mix of nature-based solutions and engineered technique) scored highest in four out of six indicators (The Royal Society, 2014). Overall, grey solutions on their own were never found to be better than a purely nature-based or hybrid approach (The Royal Society, 2014).

Nevertheless, engineered, or grey solutions have primarily been used to address the impacts of climate change (Seddon, 2018). Although they work well in mitigating vulnerabilities and reducing impacts of hazards over short periods of time, they are expensive and deliver few additional benefits outside their intended purpose (Seddon, 2018). On the contrary, nature-based solutions are affordable, effective in mitigating vulnerabilities associated with climate change and extreme weather events and they provide a number of additional ecosystem services as well as economic benefits to locals (Seddon, 2018). Coastal forests, for example, offer protection against flooding, strong winds, storm surges, high temperatures while at the same time creating habitats which support biodiversity (Seddon, 2018). Nature-based solutions have additionally been found to engage local people, which results in participatory measures which are less likely to create false senses of security (Seddon, 2018; Mitchell, 2003). It is important to consider however, that nature-based solutions may be less effective over short periods of time as the effects can take time to become apparent, may be spread over larger areas of land, and involve ecosystems that are inherently vulnerable to climate change (Seddon, 2018). In such cases, hybrid measures can serve as an appropriate intermediary. They are more affordable and often have additional positive impacts compared to grey-measures (Seddon, 2018).

Though the evidence is still in development, it is apparent that nature-based solutions can provide low maintenance, low risk and low-cost solutions to many climate change related hazards and impacts (Seddon, 2018). Overall, they help communities adapt to the effects of climate change while sequestering carbon, reducing warming and protecting biodiversity. Nature-based solutions also offer a range of additional ecosystem services compared to engineering-based approaches (Seddon, 2018). Hybrid solutions can offer appropriate opportunities to integrate nature-based solutions into existing infrastructure or as a compromise for decision makers (Seddon, 2018). Research must continue in order to prove the efficiency of nature-based solutions compared to traditional measures (Seddon, 2018).

2.2. The Socio-ecological-technological systems (SETs) Framework

The socio-ecological-technological systems (SETs) framework will be introduced as a framework to assess the potential of using different adaptation strategies in the context of urban systems (Kabisch et al., 2017; Depietri & McPhearson, 2017).

The SETs framework is a way to conceptualise urban systems through their social-ecological and technical interactions (Depietri & McPhearson, 2017; Markolf et al., 2018). This approach is applicable to climate change adaptation in urban areas as it aims to identify and overcome the limitations of socio-technological approaches, such as grey infrastructure, that have a tendency to exclude ecological functions (Depietri & McPhearson, 2017). The framework (Fig. 1) is useful in comparing a range of options available and needed to adapt to the impacts of climate change in cities. Depietri & McPhearson (2017) have used this framework to compare the pros and cons of using grey, green and blue and hybrid approaches for climate change adaptation.

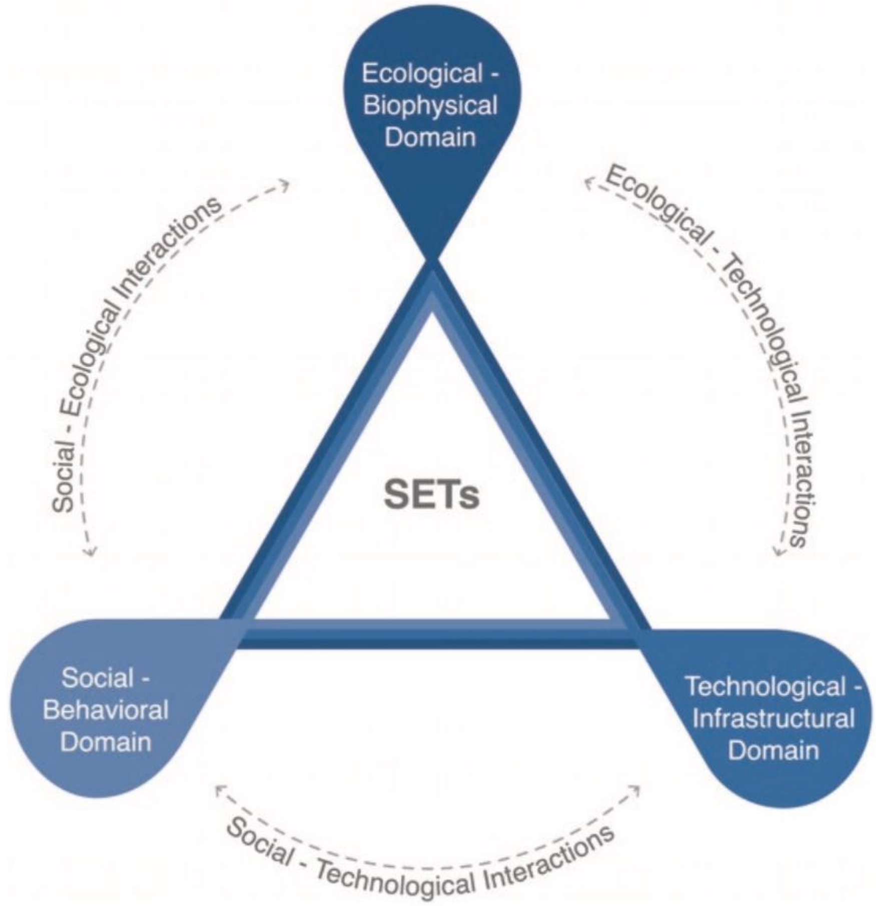

Figure 1. Conceptualisation of urban systems as social-ecological technical systems (SETs) framework. Source: Depietri & McPhearson 2017.

As shown in Table 1, grey infrastructure refers to hard engineering approaches such as seawalls, groynes or breakwaters (Depietri & McPhearson, 2017). Green and blue approaches include ecosystem-based adaptation measures, and nature-based solutions. Examples of green and blue approaches include wetland restoration, stream restoration, installation of riparian forests, etc. (Depietri & McPhearson, 2017). Hybrid approaches combine engineered infrastructure with ecosystem functions. Examples of such include green roofs, porous pavements and rain gardens (Depietri & McPhearson, 2017).

Table 1. Comparison of infrastructural adaptation measures. Source: (Depietri & McPhearson, 2017).

Grey	Hybrid	Green/Blue

Hard engineering structures	Mix of natural and engineered structures	Biophysical ecosystems and services
Limited role of ecosystem functions	Some ecosystem functioning mediated by technological solutions	Rely on ecosystem functions
Canals, pipes, dikes, groynes	Porous pavement, green roofs, rain gardens	Wetlands, riparian buffer, forests, stream restoration

As previously mentioned, traditional responses to climate change related exposures have relied on grey infrastructure. Such infrastructure is characterised by physical concrete structures such as dikes, floodgates, levees, embankments, seawalls and breakwaters. These approaches do not consider biophysical systems, ecological functioning nor the variability of climate events (Depietri & McPhearson, 2017). Considering the SETs framework, grey approaches fall within the technological domain with limited consideration of the ecological domain. Grey solutions have high maintenance costs and can have catastrophic impacts when they fail due to the heavy reliance that is placed on their success (Depietri & McPhearson, 2017). Additionally, grey infrastructure has been criticised for inhibiting normal coastal processes (Khazai, Ingram and Saah, 2007). The SETs framework shows the lack of consideration concerning the social and ecological components of urban systems associated with grey adaptation measures, by heavily relying on technological factors (Depietri & McPhearson, 2017). Social and ecological factors are dynamic and constantly changing; therefore, due to their permanence, grey solutions are not well adapted to such variability (Kallis, 2007; Depietri & McPhearson, 2017). Climate change is characterised by uncertainty and non-stationarity which grey solutions are not well adapted for (Depietri & McPhearson, 2017). Future risk is not easily taken into account in planning and building of grey infrastructure (Hallagette, 2009), which can lead to severe consequences when the grey measures fail. Examples of this include Hurricane Katrina in New Orleans in 2005 and Hurricane Sandy in New York in 2012, where the levees, seawalls and other engineered solutions failed and led to disastrous consequences.

Green and blue infrastructure rely primarily on well-functioning biophysical systems which may be restored or managed (Depietri & McPhearson, 2017). They depend on the natural functions of ecosystems and therefore fall within the ecological domain of the SETs framework. Green infrastructures include healthy reefs, coastal salt marshes, mangroves, seagrasses, dunes and forests (Depietri & McPhearson, 2017). Blue infrastructures include bodies of water such as ponds, wetlands, rivers, lakes, streams and oceans (Depietri & McPhearson, 2017). Green and blue measures have been shown to have a wide number of co-benefits, which classifies them within the social domain and strengthens the socio-ecological interactions. These measures are flexible and can be well adapted for various environmental settings. The fact that these measures can be restored and constructed in addition to mitigating climate change factors classifies them within the technological domain, strengthening the ecological-technical interactions. Several studies have shown that these natural approaches provide ecological as well as socio-economic benefits in the long-term, strengthening the socio-technological interactions (Renaud et al., 2013; Sudmeier-Rieux, 2003).

Hybrid, or green-grey approaches combine engineering and ecosystem functioning and therefore fall within the ecological and technological component of the SETs framework (Depietri & McPhearson, 2017). Hybrid approaches can also create socio-economic benefits, classifying them within the social domain of the SETs framework as well. It is important to distinguish between green or blue infrastructure which rely solely on ecosystem functions, and hybrid infrastructure where technology complements the services delivered by natural ecological functioning (Depietri & McPhearson, 2017). Hybrid approaches are suitable in urban contexts where green or blue measures are not sufficient in reducing risks and where urban planners have traditionally relied on built infrastructure. Such approaches may also be suitable for areas where space is limited and cost effectiveness is critical (Depietri & McPhearson, 2017).

Overall, through the SETs framework, it can be understood the role green/blue, grey and hybrid measures can play in different contexts. Each measure has its pros and cons. Hence, it is important to understand the local environmental conditions, the needs of vulnerable communities, and the socio-economic context in order to best make use of any particular measure. The main consideration here is that green/blue measures interlink all three domains of the SETs framework by bringing together technology, ecological functions and social benefits. This highlights the role nature-based solutions can play as an adaptation measure to climate change that also creates co-benefits to human systems. Compared to hybrid approaches, green/blue measures are cheaper and provide more co-benefits which may be better suited to the needs of local people in Dar es Salaam (Depietri & McPhearson, 2017).

This paper is therefore aimed at examining the potential for nature-based solutions to mitigate vulnerabilities to the effects of climate change in Dar es Salaam. Given the intended scope of the paper, the focus will be placed on nature-based solutions appropriate for the coast of Dar es Salaam.

2.3 An Overview of Nature-based Solutions with Potential for Increasing Adaptation Capacity in Coastal Urban Areas

Recently, cities have responded to climate change by focusing on mitigation (i.e. reduction of greenhouse gas emissions) over adaptation (Wamsler, 2014). However, because urban disasters have been increasing exponentially, resulting in large-scale human and economic losses, there is an urgent need for adaptation measures (Wamsler, 2014; Kabisch et al., 2017). Adaptation measures include long-term strategies aimed at reducing exposure, susceptibility and improving the capacity of vulnerable communities. Such measures are therefore precautionary and anticipatory in principle (Depietri & McPhearson, 2017). Climate change adaptation in cities has traditionally taken place through implementation of grey infrastructure (Kabisch et al., 2017). This section will explore the role nature-based solutions can play in adapting cities to the effects of climate change. The nature-based solutions below are chosen for closer scrutiny and potential application because the natural environment of the study area favours their existence. Mangroves, sand dunes, seagrass and coral reefs are all dominant features of the Tanzanian coastline (Ochieng & Erftemeijer, 2003). While they are not being considered or used as nature-based solutions, their existence in the study area (in some cases in degrading states) means that their introduction and potential use in the area will conform with and be supported by the local biophysical environment.

2.3.1 Mangroves

Forested wetlands are the most common vegetative cover along tropical coastlines. They cover approximately 180,000 km^2 in tropical and subtropical zones (Chen & Shih, 2019). Mangrove forests are a type of wetland ecosystem that provide a wide range of values to both ecosystems and humans (Chen & Shih, 2019). They provide diverse ecological functions, such as serving as habitats and nesting grounds for many species of birds and fish and being home to a wide range of biodiversity (Chen & Shih,2019). They are also useful for human populations as they serve as a source of income and employment for fishing communities, fuelwood and protection from weather extremes and natural hazards (Petrosian et al., 2016; WWF, 2020).

Mangroves protect coastal areas by reducing the impact of, or can fully eradicating, coastal flooding while providing livelihood benefits for local communities (IUCN, 2019). The World Bank estimated that floods would be 25% more damaging without the presence of mangroves (World Bank, 2018). Mangroves, where high in density, reduce the height and energy of waves, diminishing their ability to erode sediments (Spalding et al., 2014). As tides move towards the coast, they pass through mangrove forests and lose energy. At the same time, waves lose their ability to scour the seabed and carry away sediments, which would otherwise aggravate erosion rates (Spalding et al., 2014). By slowing the flow of water, mangroves allow for suspended and trapped sediments to deposit, further reducing rates of erosion. Additionally, mangrove soils are rich in organic matter and through their dense root network, they protect the soil from eroding forces (Spalding et al., 2014). By capturing coastal sediments, not only do mangroves reduce erosion, but they also allow for soil to build up over time. The roots of the mangroves consequently grow; further pushing up the soil, which allows them to keep up with sea-level rise. Furthermore, mangroves can reduce salt-water intrusion, which threatens freshwater supply (Spalding et al., 2014; Hilmi et al., 2017).

Mangroves grow well in areas where freshwater mixes with seawater and where sediment is composed of accumulated deposits (Selvam, 2007). Mangroves flourish in coasts dominated by shallow marine sediments. They work best in areas where wave energy and wind speed are less and in areas with heavy sediment loads. Therefore, they work well as a buffer between land and sea or in river deltas characterised by brackish water (Selvam, 2007).

Mangrove forests are threatened by urban development, overexploitation and land use changes (Petrosian et al., 2016; Chen & Shih, 2019). Estimates show that 35% of mangrove forests have been lost over the past 20 years, resulting in serious ecological and economic losses (Chen & Shih, 2019).

2.3.2 Coral Reefs

Coral reefs have shown to reduce wave energy by 97% (Ferrario et al., 2014). Reef crests alone are responsible for decreasing about 86% of wave energy (Ferrario et al., 2014). Comparisons show that coral reefs provide comparable wave attenuation levels to traditional grey measures (Ferrario et al., 2014). Coral reefs therefore act as buffers which protect shorelines from waves, storms and floods. Similar to mangroves this helps reduce loss of life, property, erosion and damage to ecological systems (NOAA, 2019; Zhao et al., 2019). About 200 million people depend on coral reefs as natural protection mechanisms (Coral Reef, 2020). Degradation of coral reefs would result in high mitigation and adaptation costs. In the absence of reefs, coastal communities become more vulnerable to wave action, violent storms and flooding (NOAA, 2019).

With increases in the occurrence of intense storms being expected as a result of climate change, coral reefs will be of great importance due to their wave attenuation properties (Reguero et al., 2018). Reefs also promote biodiversity and contribute to local economies through tourism and conservation value. Coral reefs are negatively affected by eutrophication and should therefore avoid river deltas (Silva et al., 2017). Overall, investments in coral reefs are beneficial as adaptation and mitigation measures to strengthen the first line of coastal defence (Ferrario et al., 2014).

2.3.3 Dunes

Sand dunes are a natural buffer from wind and waves along coastal areas (Montanari, 2017). They are able to absorb incoming energy from storm surges and stabilise the land, reducing coastal erosion (Montanari, 2017). Sand dunes also serve as stocks of sand which can replenish eroded soil following storm events (Montanari, 2017). Dunes are highly adaptive and tend to move inland with sea-level rise (Montanari, 2017). Dunes become less adaptive in the presence of infrastructure as this reduces their ability to form in accordance with environmental conditions (Montanari, 2017). Where appropriate however, dunes can serve as an effective front line of defence for land located along coastlines. Sand dunes have also been shown to act as a filter system, which reduces saltwater intrusion (Marconi et al., 2009). If managed properly, sand dunes can play a role in mitigating the effects of sea-level rise, increased storm events and saltwater intrusion (Hanley et al., 2013; Marconi et al., 2009).

2.3.4 Seagrass

Globally, seagrass beds account for 10% of the ocean's capacity to store carbon while occupying only 0.2% of the seafloor (UN Environment, 2019). Compared to rainforests, seagrass can capture atmospheric carbon up to 35 times faster than tropical rainforest (UN Environment, 2019). In addition to mitigating climate change through carbon sequestration, they provide ecosystem services that range from providing habitats to endangered species all the way and reducing rates of erosion (Ondiviela et al., 2014).

Similar to mangroves and reefs, submerged vegetation such as seagrass beds provide habitat for diverse numbers of species, making them key for biodiversity conservation (UN Environment, 2019; Ochieng & Erftemeijer, 2003). Seagrass beds also serve as nursing and breeding grounds for marine fish and crustaceans, which are economically important to local communities whose livelihoods depend on small scale fishing (Ochieng & Erftemeijer, 2003).

Seagrass can reduce the velocity of waves as well as dissipate wave energy and stabilise sediment (Ondiviela et al., 2014). Seagrasses are also key trophic transfers to adjacent habitats (Costanza et al.,1997) such as salt marshes and reefs (Ondiviela et al., 2014). They are therefore appropriate as transition vegetation between mangroves and coral reefs for example, which would increase the resilience of the ecological system while providing the above-mentioned ecosystem services.

Seagrass should not be present around river deltas as agricultural activities result in nutrient influxes that can cause eutrophication, ultimately suffocating the seagrass (Ochieng & Erftemeijer, 2003). Seagrasses are also threatened however by warming ocean temperatures, increased storms and sea level rise. If anthropogenic induced threats in coastal areas occur too fast for seagrasses to adapt, they may lose their coastal defence services (Ondiviela et al., 2014).

2.4 Required Environmental Conditions

As with any multitude of engineering projects, certain conditions need to be met for nature-based solutions to be successful. In the case of nature-based solutions, such conditions are heavily environmental. For example, wetlands usually thrive in environments exposed to lower wave intensities than beaches and dunes (Bridges et al., 2015). Thus, it is important to consider biophysical characteristics required for different nature-based solutions. In coastal areas, the primary forcing factors, or conditions are wave height and period, water level and current (Bridges et al., 2015). Sedimentary characteristics such as sediment size and material as well as supply and erosion rates determine how sensitive a feature may be and how well it can recover from impacts (Bridges et al., 2015). Aquatic conditions such as levels of salinity also play a structural role in determining what sorts of vegetation can grow in certain locations. Finally, geographic conditions such as the extent of land needed for different measures must also be considered. Although it is outside the scope of this study to apply all previously identified characteristics to the GIS analysis in this paper, a more in-depth study should be aware of these important concepts

3. Study Area

Tanzania is located along the eastern coast of Africa (Fig. 2a). The country shares borders with Uganda and Kenya through Lake Victoria (Mascarenhas et al., 2019). The Tanzanian coastline spans 800km (Fig. 2b) and is characterised by a shallow and relatively narrow continental shelf bordering the Indian ocean (Ochieng & Erftemeijer, 2003). The coastline is characterised by extensive coral reefs, limestone cliffs, beaches, mangrove forests and sand dunes, which grow in an interconnected ecosystem (Ochieng & Erftemeijer, 2003).

The majority of the population's livelihoods are dependent on climate-change sensitive agriculture, making Tanzania particularly vulnerable to climate change (Paavola, 2003). Dar es Salaam (Fig. 2c) was chosen as the study area because it is a key coastal city facing a high infrastructure deficit and may need alternative adaptation measures in order to address vulnerabilities to climate change (Mguni, Herslund & Jensen, 2015). Coastal livelihoods are also heavily dependent on activities that are hinged on healthy ocean and aquatic ecosystems such as fishing, the harvesting of mangroves for fuel wood, ocean-faring tourism, (WWF, 2020). These are activities whose viability, and hence impact on local livelihoods are directly linked to the vulnerability of coastal areas to the impacts of climate change.

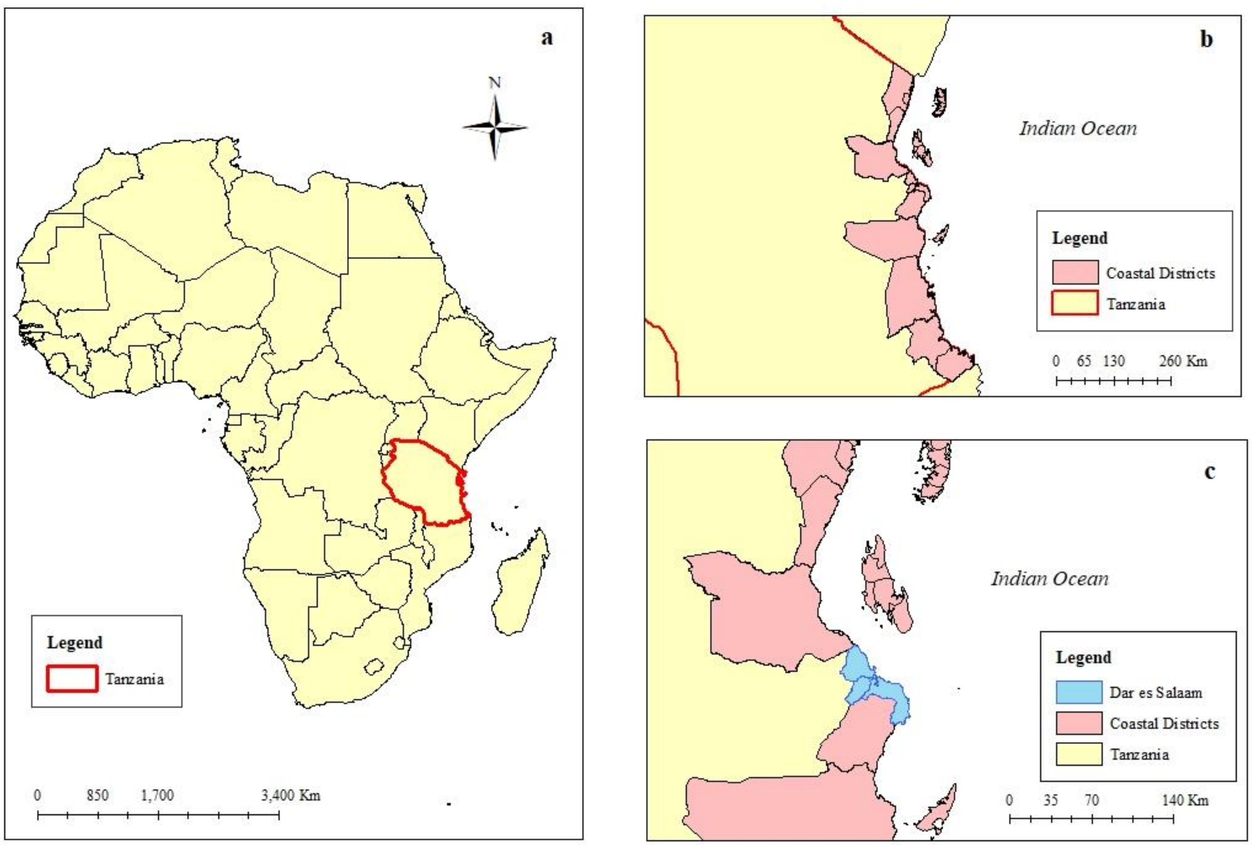

Figure 2. Location of study area. Tanzania at a country level (a); Tanzania's coastal districts (b); Dar es Salaam situated within the coastal districts of Tanzania (c).

3.1 Physical Characteristics

Dar es Salaam is the former capital of Tanzania. The city is located between latitude 6.45°S and 7.25°S, and longitude 39°E and 39.55°E. Dar es Salaam covers an area of 1,350 km^2, occupying 0.19% of the Tanzanian mainland (START, 2011). It stretches 100km between the Mpiji River to the North and past the

Mzinga River in the South. Its Eastern coast falls along the Indian Ocean (START, 2011). The city serves as the main port and is recognised as the most important commercial and manufacturing centre in the country (Kiunsi, 2013). The city can be divided into three municipalities, namely Ilala, Kinondoni, and Temeke, which are divided into 74 local wards (Kebede & Nicholls, 2011). Topographically, three distinct areas can be identified in Dar es Salaam: the lowlands, falling along the Indian Ocean shores and the river valleys of the four principle river systems, the middle plateau and the hilly areas in the north and west of the city (Kiunsi, 2013).

3.2 Socio-economic Characteristics

The population of Dar es Salaam is currently about 6.7 million and it is projected to receive megacity status by 2030 (Todd et al., 2019). About 80% of the city's population lives in unplanned settlements (Kiunsi, 2013). Most of the city's growth has occurred along the central and northern part of the coastline (Kebede & Nicholls, 2011). As the country's key economic and administrative centre, Dar es Salaam is the most important city in terms of commerce and manufacturing (Kebede & Nicholls, 2011; START, 2011). The main economic activities in and around Dar es Salaam include the mining of sand, gravel stones, limestone and salt extraction. In addition, urban agriculture, fishing, recreation and tourism play strong economic roles (START, 2011). Fishing occurs mainly by small scale fishermen as inland fisheries are rather limited (START, 2011). Recreation and tourism occur mainly along the coast and the neighbouring island of Dar es Salaam (START, 2011). About 60% of the population relies on the informal sector as their primary source of income (Kiunsi, 2013). This includes petty trading, urban agriculture, fishing, and physical work (Kiunsi. 2013). Public services such as water supply, sanitation, waste management, road maintenance and stormwater drainage are relatively poor (Kiunsi, 2013). A small proportion of areas have adequate storm drainage and in addition, the city has a water deficit (Kiunsi, 2013).

3.3 Morphological Characteristics

The beach and shoreline along the coast of Dar es Salaam is comprised of sand dunes and tidal swamps (START, 2011). The coastal plain is made up of limestone and extends 10km to the west of the city, 2-8km to the north and 5-8km to the south (START, 2011). There are a series of steep U-shaped valleys and an upland plateau with an altitude of 100-200 meters (START, 2011).

3.4 Climate Overview

The climate is characterised by hot and humid days throughout the year with an average temperature of 29°C (Kiunsi, 2013). Maximum and minimum average daily temperatures are 35°C and 25°C, respectively (Kiunsi, 2013; Kebede & Nicholls, 2011). Precipitation in Dar es Salaam is concentrated in two rainy seasons yielding between 1,000 and 1,300 millimetres per year (Kiunsi, 2013; Kebede & Nicholls, 2011). Rainfall is distributed in two rainfall periods; the long rainy season from mid-March to end of May, and the short rainy season from mid-October to late December (START, 2011). Rainfall in this area is largely influenced by El Nino Southern Oscillation (ENSO), tropical cyclones, easterly waves and the Congo air mass (START, 2011).

It is predicted that by 2080, temperatures are expected to be 2.5°C to 4.5°C warmer (Kiunsi, 2013). Precipitation is also projected to increase in all rainfall seasons with coastal areas experiencing the greatest increase (Kiunsi, 2013). Climate change is expected to increase the frequency of extreme weather events throughout Tanzania including rainstorms, droughts, coastal flooding and sea level rise (Kiunsi, 2013).

3.5 Climate Change Hazards, Exposure and Vulnerabilities

Climate change increases Dar es Salaam's vulnerability to climate impacts. Vulnerability refers to the "degree to which a system's attributes of concern are susceptible to, and unable to cope with, the adverse effects of hazards over a period of time or temporal reference" (Bridges et al., 2015, p.50). In the context of climate change, vulnerability can be defined as the "capacity to be wounded" by climate change impacts (Paavola, 2003). Coastal vulnerability refers to people and places that are susceptible to disturbances resulting from coastal hazards, which can pose significant threats to coastal physical, economic, and social systems. (Bevacqua, Yu & Zhang, 2018).

In the case of Dar es Salaam, 80% of the city falls within the Low Elevation Coastal Zone, which lies below 10 metres above sea level (Kebede & Nicholls, 2011). Kebede and Nicholls (2011) analysed Dar es Salaam's vulnerability to sea-level rise. They estimated that about 8% of the population lies in a low elevation zone below 10m contour line, inhabited by over 143,000 people with economic assets estimated at US$168 million (Kebede & Nicholls, 2011). The number of people and value of economic assets at risk due to sea-level rise is expected to increase by 2030 (Kebede & Nicholls, 2011).

Certain parts of Dar es Salaam are experiencing coastal erosion due to sea level rise and storm surges (Kiunsi, 2013; Kebede & Nicholls, 2011). Coastal erosion and salt-water intrusion are major issues for Dar es Salaam's coastal areas as they negatively impact ecosystem services and the livelihoods of coastal communities (START, 2011). Residents of coastal wetlands along the coast of Dar es Salaam that have experienced saltwater intrusion have reported extensive damage to coastal infrastructure (START, 2011).

The most vulnerable populations are those living in unplanned settlements around river valleys and the Indian Ocean shoreline (Kiunsi, 2013; START, 2011; Kebede & Nicholls, 2011). Studies by the Pan-African START Secretariat assessing perceived risks by local communities ranked flooding as the greatest threat (START, 2011). Flooding in Dar es Salaam is exacerbated by poor planning, the poor drainage system and housing conditions as well as the limited capacity of local communities to adapt to flooding (Kiunsi, 2013). Climate change is expected to increase sea level rise, the frequency of storms and floods, which poses major threats to the coast of Dar es Salaam (Kiunsi, 2013; START, 2011; Watkiss et al., 2011).

There is little experience in terms of climate change adaptation in Dar es Salaam (Kiunsi, 2013). Dar es Salaam has seen little protection measures being taken. Certain areas have implemented groynes and seawalls (Brown, Kebede & Nicholls, 2017). These have been degraded however and expected costs for 1-m sea-level rise reach US$337 million. Predictions also show that an average of 400m landward retreat would take place in Dar es Salaam under a 1-m sea-level rise (Brown, Kebede & Nicholls, 2017).

The lack of climate change adaptation measures despite the urgency and previously experienced consequences is associated with challenges relating to inadequate institutional capacity, coordination and information flow (Kiunsi, 2013; START, 2011).

4. Data & Methodology

This section will outline the data and methodology used in order to address the research questions. The section will begin with a description of the key informant interview, followed by a description of the geospatial methods used to assess the suitability of locations for the implementation of nature-based solutions.

4.1 Key Informant Interview

The key informant interviewed in this thesis is the Senior Environmental Officer at the Environmental Division of the Vice President's Office (VPO) in Tanzania. The Environmental division at the VPO oversees providing policy guidance, coordination, expertise and services for sustainable environmental management and development in Tanzania. The division also supervises operations by the National Environment Management Council, issues reports of the State of Environment and coordinates the implementation of the green growth and climate resilient development agenda. The Officer oversees issues relating to climate change vulnerability along the coast of Dar es Salaam, making them one of the most suitable informants for this thesis.

The key informant interview was conducted by means of a semi-structured questionnaire. The questionnaire was designed to capture key information on the types of vulnerabilities the coast of Dar es Salaam faces due to climate change; the location of the most vulnerable wards; the most frequent and severe vulnerabilities at each site; current measures being taken and the effectiveness of said measures. The survey questions can be found in Appendix I.

A total of eight possible key informants were contacted to take part in the semi-structured questionnaire; however only the officer described responded. Follow-up messages were sent out but were unsuccessful. Regardless, the Senior Environmental Officer at the VPO is one of the most informed people regarding climate vulnerabilities in coastal Dar es Salaam. The Officer provided authoritative insight into the vulnerabilities along the coast of Dar es Salaam. This Officer helped in identifying specific wards in Dar es Salaam and the respective threats each vulnerable ward faced due to the impacts of climate change.

4.2 Geospatial Analysis

Geospatial analysis was used to model the suitability of coastal Dar es Salaam for the potential implementation of nature-based solutions to address climate change induced vulnerabilities. The vulnerabilities were derived from the key informant interview described in section 4.1.

Suitability modelling is a process used to solve a variety of spatial location problems. These models weigh locations relative to each other based on given criteria, and a variety of overlay procedures (Bonham-Carter, 1994) are used to combine the weighted results for specific input datasets into a combined suitability output for the set of defined criteria (ESRI, 2020). Suitability models are well established and have been used for a range of geospatial location challenges such as for making informed decisions about the most and least propitious areas locations for specific purposes (Bajjali, 2018). This allows decision-makers to evaluate different planning options based on pre-selected criteria.

The suitability analysis procedure follows five steps: i) identifying goals and site's issues; ii) collecting data and establishing criteria; iii) ranking and weighing criteria; iv) integrating and analysing the data into geographic information systems (GIS); v) evaluating outputs. The following section will describe the suitability analysis procedure used in this thesis.

4.2.1 Data Collection & Preparation

All the data obtained for the geospatial analysis was obtained through open data sources. An overview of all the GIS data used in this thesis is provided in Table 2. All downloaded data was obtained in vector format except for the digital elevation model of Tanzania and the land cover data. The most commonly used data sources were the Regional Centre for Mapping of Resources for Development - RCMRD (https://www.rcmrd.org/) and MapCruzin-Data Research & GIS Project Specialist (https://mapcruzin.com). The RCMRD is a geoportal platform providing open geospatial datasets for the Eastern and Southern Africa region. MapCruzin is an independent firm specialising in professional data research and analysis. The specific shapefiles downloaded from MapCruzin and used in this thesis were derived from OpenStreetMap (https://www.openstreetmap.org/)and made available by MapCruzin. The digital elevation model for Tanzania was downloaded from ArcGIS online and the census wards were obtained from Humanitarian OpenStreetMap - HOT (https://www.hotosm.org/). Additional datasets were used in order to create supporting maps. The overview of these datasets can be found in Appendix A.

Table 2. Overview of GIS data used in the suitability analysis.

File Name	File Type	Source	Description
Tanzania_SRTM 30meters	Raster	ArcGIS Hub (2018)	Elevation of Tanzania. This data set was useful in analysing vulnerable wards as it displayed the elevation in all of Dar es Salaam. From this dataset, it could be seen which areas were the most low-lying and therefore most vulnerable and susceptible (Appendix G).
Tanzania_LandCover_2010	Raster	RCMRD (2010)	Land Cover of Tanzania (Appendix B). This dataset provided an overview of the land cover in Dar es Salaam, it was useful in showing that the most vulnerable wards were also the most urbanised and built-up.
Roads	Vector	MapCruzin (2020)	Roads of Tanzania. This dataset was useful in showing areas in which human settlements are most dense,

			especially in relation to waterways and proximity to the coast (Appendix C).
Tanzania Seagrass	Vector	RCMRD (2015)	Coastal vegetation of Tanzania. This dataset was the primary dataset used in the suitability analysis. It provided an overview of existing coastal vegetation, which was used in order to create the criteria decision for the suitability analysis (Appendix E).
2012 Census Tanzania Wards Shapefiles	Vector	HOT (2012)	Census wards of Tanzania. This dataset subdivided regions of Tanzania into census wards. This was imperative to be able to map vulnerable areas, especially in regard to the information provided by the key informant and additional literature (Fig 3).
Waterways	Vector	MapCruzin (2020)	Major waterways of Tanzania. This dataset proved useful in identifying areas located further inland that may also be prone to flooding due to their proximity to major waterways crossing the city (Appendix C).

Data preparation was required before being able to conduct any analysis. First, all datasets were projected to a common coordinate system. The coordinate system used was WGS1984. All the datasets contained data for the whole of Tanzania. In order for the data to be focused on Dar es Salaam, all the data needed to be clipped to the extent of Dar es Salaam. For the vector data, this was done by using the clip function. For the raster data, this was done through the extract by mask tool. The dataset for coastal vegetation required a different approach in order to be clipped to the extent of Dar es Salaam. Due to the fact that most coastal vegetation, represented by polygons, were not connected to the coast, the cut polygon feature had to be used in order to limit the coastal vegetation of the entire country to Dar es Salaam. Once all datasets were correctly projected on a common coordinate system and clipped to the necessary extent, vector features which were going to be used in the suitability analysis had to be converted to raster. This was done with the feature to raster tool.

4.2.2 Criteria Establishment

The focus of this thesis is on the potential for using nature-based solutions to mitigate vulnerabilities to climate change along coastal Dar es Salaam. Because most nature-based solutions would be located either along the coast or in the ocean, the criteria heavily depended on considering existing coastal features.

Criteria was established based on the location and type of existing coastal features found in the Tanzania Seagrass dataset (Appendix E). This dataset provided the location and area of open water, turbid water, sand, coral reefs and submerged vegetation. Based on the type of feature, criteria were established to determine the potential suitability of the four nature-based solutions being investigated in this thesis: mangroves, seagrass, dunes and coral reefs. The criteria were therefore composed of the location of open water, turbid water, sand and coral reefs. These features were subsequently ranked and weighed in terms of potential suitability for the four nature-based solutions. The ranking was informed by academic literature (Selvam, 2017; Silva et al., 2017; Montanari, 2017; Ochieng & Erftemeijer, 2003) describing suitable and unsuitable locations for mangroves, coral reefs, sand dunes and seagrass.

In order to rank and weigh the data, the weighted overlay function was used. The weighted overlay function was used over the weighted sum as it allows for the reclassification of values onto a common scale. This in turn allows for certain features to be prioritised over others. For each of the criteria (coastal features), ranks were assigned on an evaluation scale of one to five. One represented least suitability while five represented the highest suitability. Since the coastal features used in the criteria were within a single raster layer, an automatic influence of 100% was assigned to the raster layer. A unique weighted overlay was conducted for each of the four nature-based solutions. An overview of the ranking scheme for each nature-based solution is provided below (Table 3).

Table 3. Ranking Scheme for the suitability analysis.

Nature-based solution	Criteria	Weight
Mangrove	Open water	3
	Turbid water	5
	Sand	1
	Coral reef	2
	Submerged vegetation	4
Seagrass	Open water	4
	Turbid water	5
	Sand	1
	Coral reef	2
	Submerged vegetation	5
Coral reef	Open water	4

	Turbid water	2
	Sand	1
	Coral reef	5
	Submerged vegetation	3
Dune	Open water	1
	Turbid water	2
	Sand	5
	Coral reef	1
	Submerged vegetation	1

As previously mentioned, the ranks were assigned based on academic literature and the location of coastal features. For example, Salvam et al. (2017) states that mangroves grow best in areas with high sediment loads and low wave energy. Areas of turbid water and where submerged vegetation are found were therefore assigned a high suitability. Areas dominated by the presence of sand (inland beaches) and coral reefs were assigned a low weight. Due to the presence of coastal islands certain areas in the open water could have been suitable for mangroves and as a result a moderate weight was assigned. This procedure was applied to coral reefs (Silva et al., 2017), seagrass (Ochieng & Erftemeijer, 2003) and sand dunes (Montanari, 2017).

4.3.3 Methodological Limitations

The main shortcoming is the lack of fieldwork/ground-truthing conducted. This limits the accuracy of the results; however, the fact that a key informant working in Dar es Salaam and with extensive field knowledge provided valuable insight helps address this point.

Also, the suitability analysis was conducted on the basis of existing vegetation cover along the coast. As stated in the methodology section, higher ranks were given to existing vegetation types that are most suitable for the respective nature-based solution. The GIS analysis is quite basic however in that it does not consider factors such as salinity, water depth, wave height, water temperature, previous sea-level rise and other factors which would have an effect on the spatial appropriateness of certain nature-based solutions. Therefore, the results of the study would benefit from a more in-depth GIS analysis conducted in order to more precisely identify potential areas of implementation within the suitable zones identified in this thesis.

5. Results

In this section, the results of the thesis will be presented in accordance with the research questions. The section will begin with the results of the key informant interview followed by the suitability analyses conducted for each of the four potential nature-based solutions.

5.1 Results from key informant interview

The Officer identified three main threats affecting coastal regions of Dar es Salaam. These include flooding, coastal erosion, and infrastructure damage (see Table 4 & Fig. 3). Lack of adaptation measures to climate change was reported to be the main reason for the vulnerability of coastal areas to climate change (especially to the flooding threat). Other factors identified as reasons for vulnerability include higher rates of observed erosion, stronger wave action and geomorphological characteristics (see Table 4). The current measures for dealing with existing vulnerabilities are primarily grey-infrastructure-based, including increasing the depth of rivers, upgrading unplanned settlements, building storm drains and installing groynes/seawalls (see Table 4). The use of nature-based solutions is not very common - currently limited to only two wards - Mbweni and Kunduchi. The key informant observed that there is room for nature-based solutions to contribute as a sustainable portfolio of approaches to climate adaptation and resilience building in coastal communities of Dar es Salaam.

Table 4. Survey results identifying specific vulnerabilities to climate change along the coast of Dar es Salaam.

Vulnerable Areas	Specific Threats	Reason for Vulnerability	Current Adaptation Measures
Jangwani	Flooding	Lack of adaptation measures	Increase depth of Msimbazi river, Upgrading unplanned settlements
Kinondoni	Flooding	Lack of adaptation measures	Increase depth of Msimbazi river, Upgrading unplanned settlements
Kurasini	Flooding	Lack of adaptation measures	Increase depth of Msimbazi river, Upgrading unplanned settlements
Manzese	Flooding	Lack of adaptation measures	Increase depth of Msimbazi river, Upgrading unplanned settlements
Mikocheni	Flooding	Lack of adaptation measures	Diversion of storm drainage

Kawe	Coastal Erosion	High rates of coastal erosion	Installation of groynes & seawalls
Kivukoni (Ocean Road)	Coastal Erosion	High rates of coastal erosion	Installation of groynes & seawalls
Msasani (Oyster Bay)	Coastal Erosion	High rates of coastal erosion	Installation of groynes & seawalls
Kigamboni (Peninsula)	Infrastructural Damage	Geomorphological characteristics	None
Mbweni (Ununio)	Infrastructural Damage	High wave action	Planting mangroves
Kunduchi	Coastal Erosion, Infrastructural Damage	High rates of coastal erosion, High wave action	Installation of groynes & seawalls, Planting mangroves

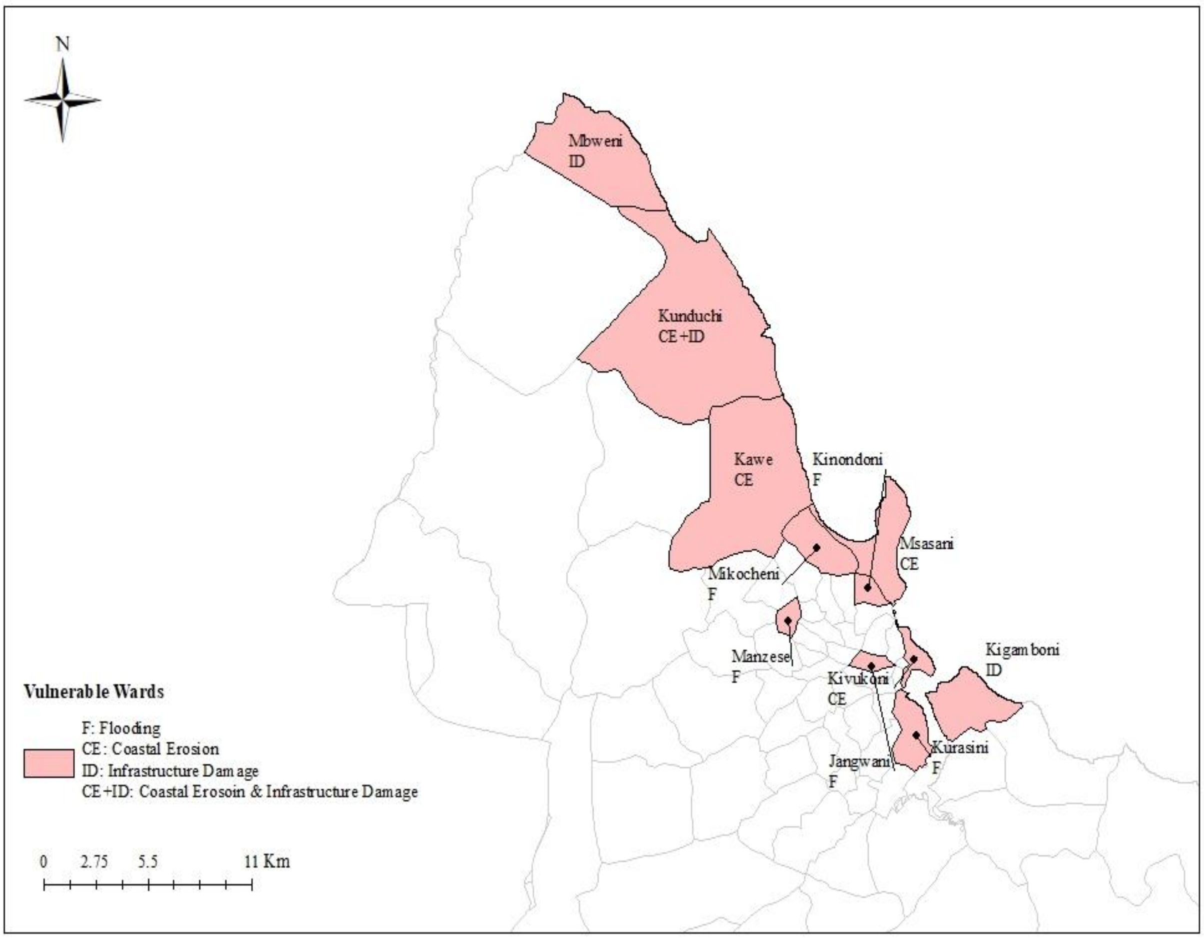

Figure 3. Map showing the vulnerable wards of Dar es Salam and their respective threat/vulnerability.

Making use of various additional datasets can shed light on the pressures faced in certain districts and help better understand the pressures contributing to coastal vulnerability and the potential role nature-based solutions. For example, Appendix B overlays the vulnerable wards on the land use of Dar es Salaam.

Through this figure, it can be seen that the majority of the vulnerable wards are dominated by settlement and urbanised land. The continuous urbanisation of Dar es Salaam exerts pressure on the land closest to the coast. Additionally, this leads to the exploitation of resources closest to the coast, which can result in unwanted erosion and depletion of natural resources. Due to the high concentration of urban infrastructure along the coastline, sea-level rise and flooding can lead to infrastructure damage. Additionally, as shown in Appendix G, it can be seen that all the vulnerable wards lie at the lowest elevation of the entire city. This exacerbates the risk and effect of flooding and increases the probability of coastal erosion and the exposure of infrastructure to be damaged.

In combination with being located in a low-lying elevation zone, waterways travel throughout the city. Before reaching the ocean, they pass through areas with high densities of urban infrastructure. Appendix C shows the road and waterways network. These waterways can exacerbate flooding within the city and cause infrastructure damage along with erosion of riparian buffers.

5.2 Results from suitability modelling of nature-based solutions

The following section will present the results of the geospatial suitability analysis for mangroves, coral reefs, dunes and seagrass.

5.2.1 The suitability of mangroves as a nature-based solution in coastal areas of Dar es Salaam

As previously mentioned in the literature review, mangroves are biologically diverse ecosystems which reduce impacts from flooding. They do so by dissipating wave energy as water passes through their complex root system. This root system also serves to capture sediments, thereby decreasing rates of erosion. Given these attributes, the areas that would profit from mangrove implementation are those experiencing flooding and coastal erosion. Infrastructure damage can also be reduced through mangrove implementation, when found in close proximity to the coastline, due to the buffering capabilities of these ecosystems. Therefore, Mbweni, Kunduchi, Kawe, Kinondoni, Kivukoni, Kurasini and Kigamboni would all benefit from mangrove implementation. Jangwani, Manezese and Mikocheni are not located close enough to the coast to potentially support a mangrove habitat.

Mangroves have been proven to mitigate the vulnerabilities and threats identified in this section. A suitability analysis was conducted in order to see where potential areas of implementation could occur along the coast. The result of the suitability analysis is presented below (Fig. 4). The most suitable areas are highlighted in dark green and the least suitable in red. According to this figure, the districts with coastal features most suitable for the potential installation/expansion of mangrove include Mbweni, Kawe, Mikocheni, Msani, outland parts of Kivukoni, Kigamboni and the waterbody between Kurasini and Kigamboni. Certain areas further into the ocean appear to be suitable. These are areas where submerged vegetation is known to be found and areas close to small islands, which may exhibit similar coastal characteristics as the mainland area.

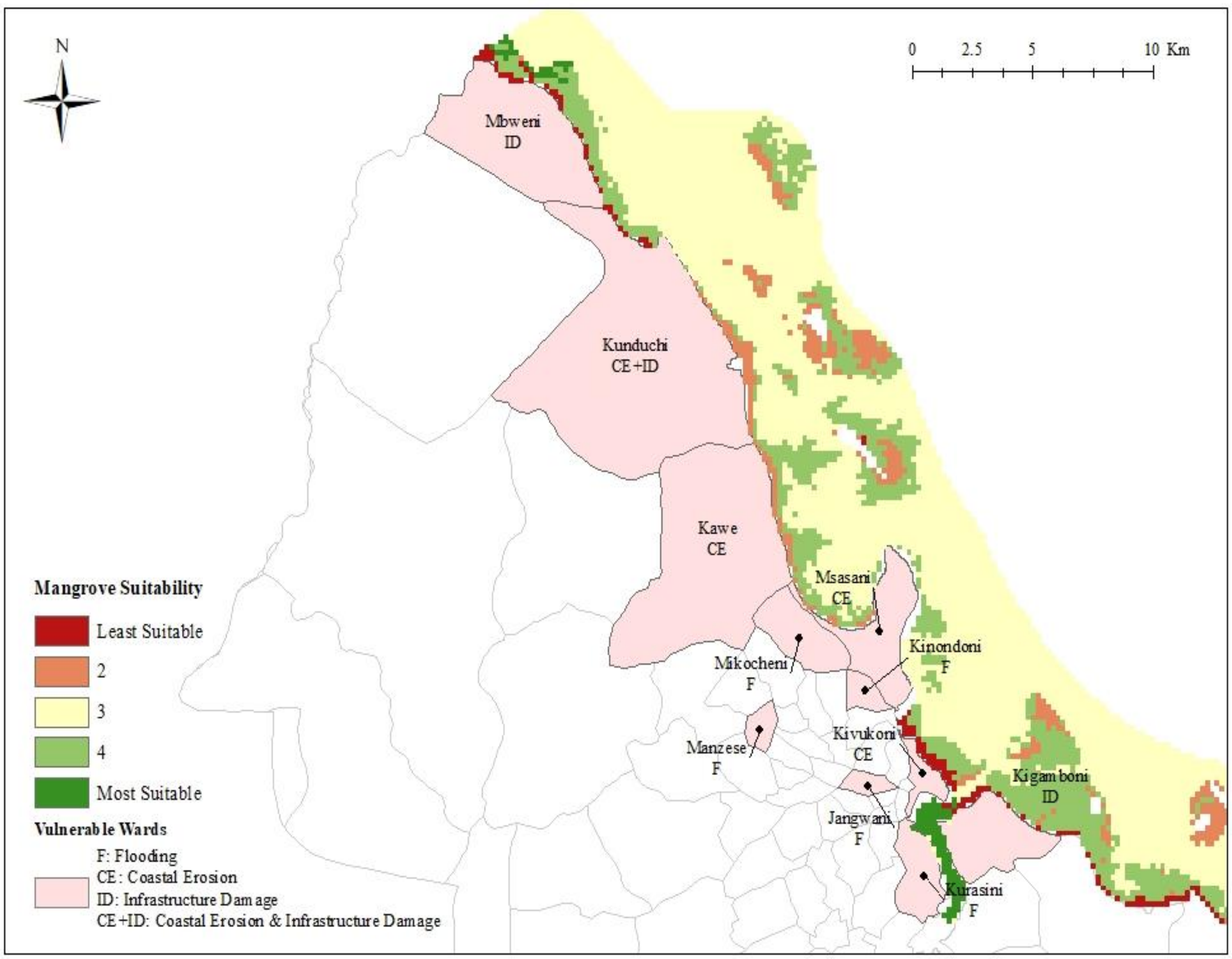

Figure 4. Mangrove suitability along the coast of Dar es Salaam with a focus on vulnerable wards.

It can be observed that mangrove suitability is highest in areas of turbid water and existing submerged vegetation. This is due to the fact that submerged vegetation refers to a number of different aquatic vegetation types, which would also be suitable for mangroves. Submerged vegetation was therefore assigned a high suitability. Turbid water is known to be suitable for mangroves, whose roots are able to trap suspended sediment and filter water. As previously mentioned in the results section, areas where coral reefs, sand and open water are present, the suitability for mangroves is lower.

5.2.2 The suitability of coral reefs as a nature-based solution in coastal areas of Dar es Salaam

The ability of coral reefs to dissipate wave energy by between 86-95% make them favourable nature-based solutions in areas that face coastal damages due to storm surges or coastal erosion as a result of high wave energy. Coral reefs therefore act as effective protective structures along coastlines. In Dar es Salaam, a number of different wards face coastal erosion and infrastructure damage due to high wave action and associated storm surges. Figure 5 provides an overview of coral reef suitability along the coast of Dar es Salaam.

The most suitable areas are found in places where coral reefs are currently present (Fig 5). These are primarily located in close proximity to the vulnerable wards, when compared to the rest of the coast. Open water (4) has also been highlighted as highly suitable, however this does not mean that coral reefs could be implemented anywhere as long as there is open water. Ocean depth, amount of light and anthropogenic activities must also be considered. The moderately suitable areas (3) already contain submerged vegetation and therefore may not be suitable for coral reef implementation or expansion. Finally, the least suitable areas, represented in red and orange are located just along coastal areas dominated by the presence of sand or turbid water, which are not suitable habitats for coral reefs.

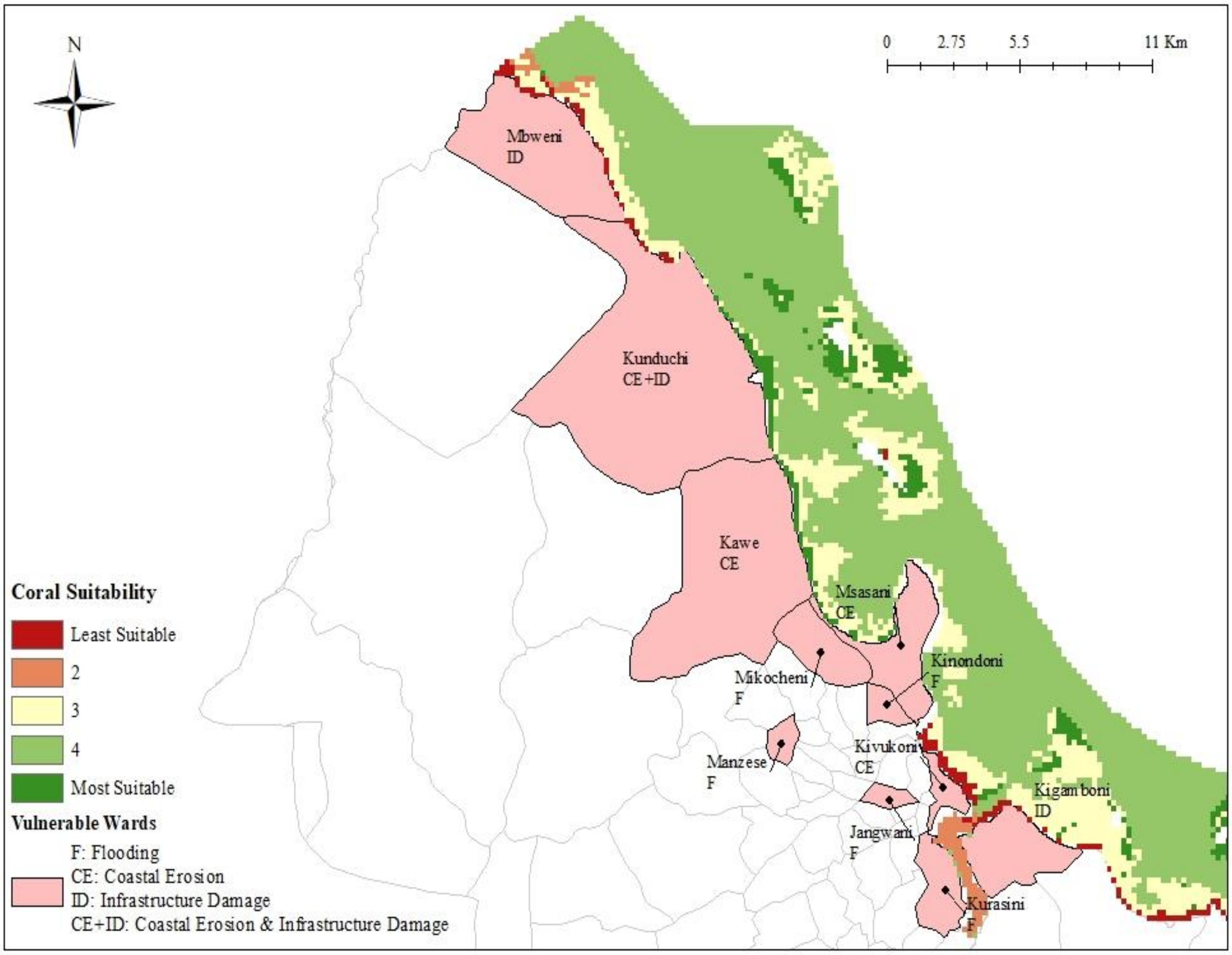

Figure 5. Suitability of coral reefs along the coast of Dar es Salaam with a focus on vulnerable wards.

From Figure 5, it can be observed that Kunduchi, Kawe and parts of Msasani have the highest suitability closest to the coast. This is promising seeing as the three districts are threatened by coastal erosion and infrastructure damage. Additionally, Kunduchi is most vulnerable to coastal erosion due to high wave action, which aligns with coral reefs' ability to reduce wave action significantly. In Kawe and Msasani, reduced incoming wave action would also aid in reducing the high rates of erosion.

Spatially speaking, coral reefs seem to have one of the highest, or largest extent of potential areas of implementation. This is because coral reefs can be found in stretches of water further away from the coast and deeper than areas close to the coastline. As a result, open water is assigned a moderately high suitability. Areas where submerged vegetation, sand and turbid water are found are assigned lower suitability, as these are less favourable habitats than areas of open water or where coral reefs already exist.

5.2.3 The suitability of dunes as a nature-based solution in coastal areas of Dar es Salaam

Sand dunes act as protective buffers from wind and waves along coastal areas. They also stabilise land, which reduces coastal erosion; and serve as sediment stocks, which can provide sand to eroded areas. Their ability to morph and move inland in response to sea-level rise make them a valuable protective structure. Additionally, considering coastal morphology, they act as the final line of defence between the ocean and coastal infrastructure. Figure 6 shows the suitability of sand dunes along the coast of Dar es Salaam. The results are based on existing areas where sand, rather than infrastructure, is found along the coastline. In this way, suitable areas are best able to support the spatial and environmental needs required.

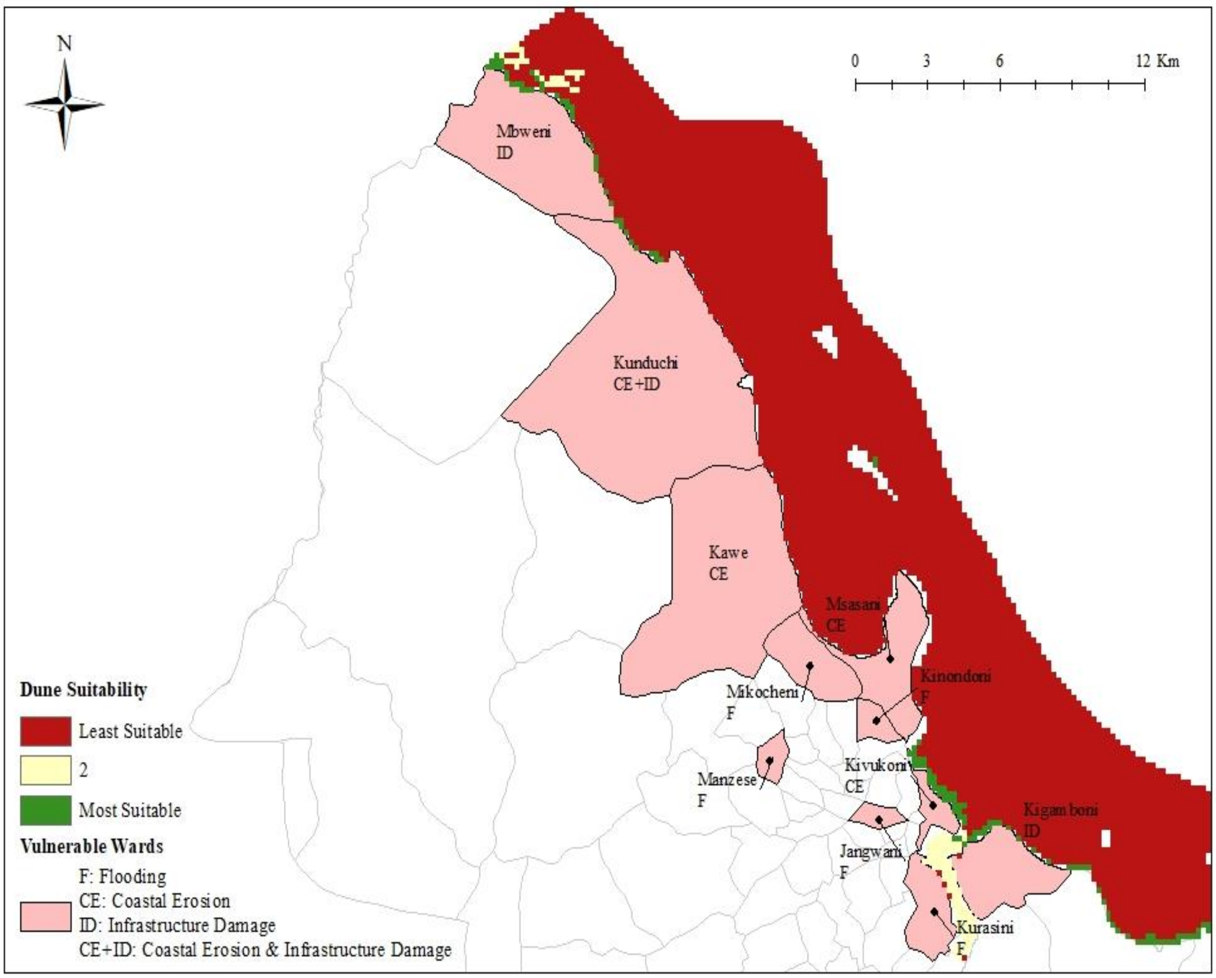

Figure 6. Sand dune suitability along the coast of Dar es Salaam with a focus on vulnerable wards.

Figure 6 shows that sand dune suitability in the north of Dar es Salaam is highest in Mbweni and the northernmost part of Kunduchi. Kivukoni and Kigamboni were also identified as suitable hotspots for sand dunes. Referring back to Table 4, Mbweni and Kunduchi face coastal erosion and infrastructure damage due to high wave action. Kivukoni and Kigamboni are threatened in the same way. Restoration/implementation of sand dunes in these areas could therefore serve to protect coastal infrastructure, stabilise erodible soil and act as a sediment supply stock to previously eroded areas.

When looking into the suitability of dunes, the suitability seems limited. It is important to consider however that the sand dataset obtained is suspected to not encompass all coastal areas present with sand, but rather the most extensive ones. This creates both pros and cons. The pros are that areas extensively dominated by sand would make the best areas of implementation due to the fact that dunes are a highly dynamic system, which require lots of space to establish themselves and also for their ecosystem services to be profited from. A small area of land would not be able to sustain a dune system and support the dunes ability to transfer sand to areas being eroded away. The same is true for areas where infrastructure is present. Therefore, the fact that the sand dataset takes such aspects into consideration is positive. Alternatively, the con is that the suitability map is limited to only certain areas. However, due to what has previously been explained this is not detrimental to the study. It can be seen from the suitability map that Mbweni, parts of Kunduchi and the majority of Kivukoni and Kigamboni show high suitability.

There are things to consider such as urban planning priorities which favour touristic areas over areas of conservation or appropriate adaptation measures which may get in the way of present socio-economic activities. A touristic beach, although extensive in space may not be practical for the implementation and/or restoration of dunes.

5.2.4 The suitability of seagrass as a nature-based solution in coastal areas of Dar es Salaam

Seagrass not only mitigates the effect of climate change by serving as a carbon sink, but it also helps reduce erosion rates by capturing drifting sediments. Seagrass beds can also reduce incoming wave energy. Figure 7 shows the suitability of seagrass along the coast of Dar es Salaam.

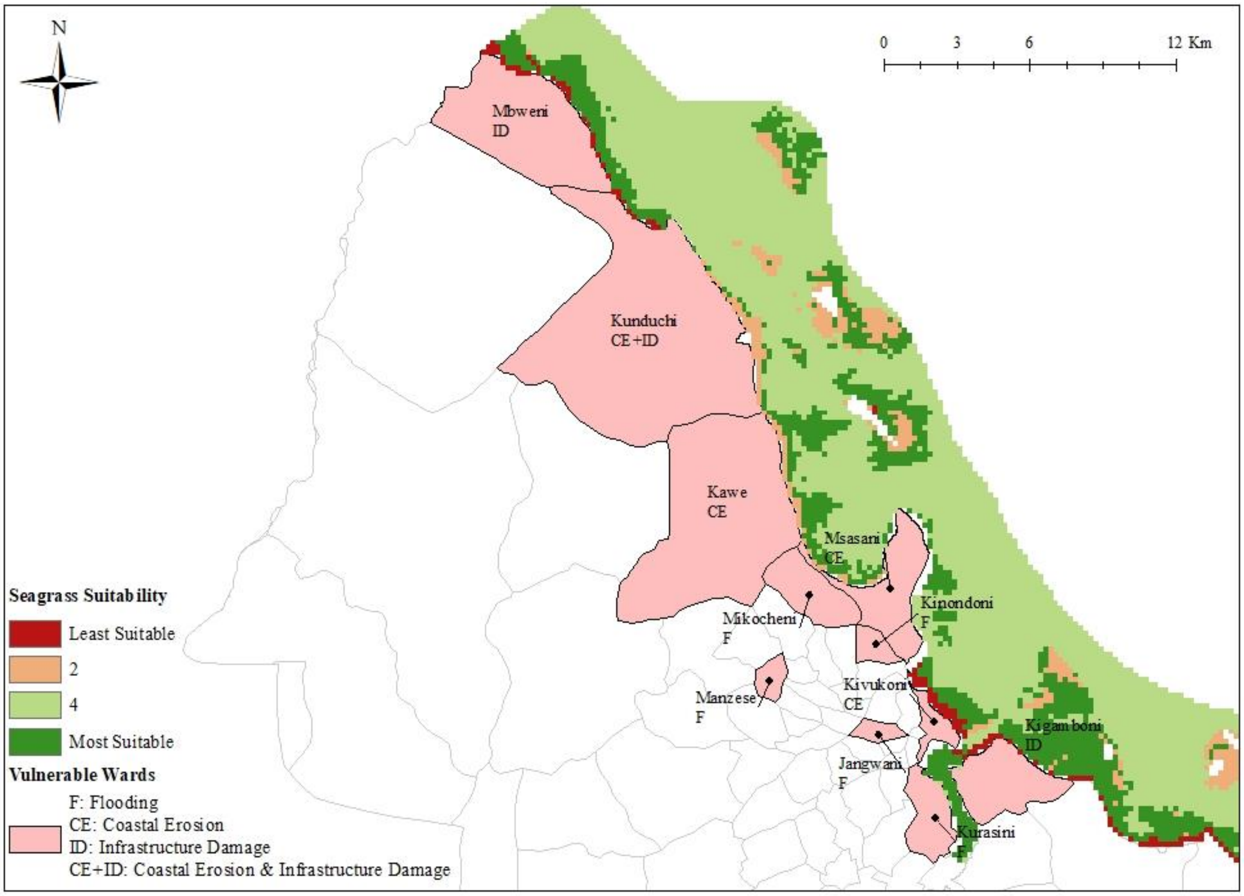

Figure 7. Seagrass suitability along the coast of Dar es Salaam with a focus on vulnerable wards.

Due to its ability to flourish not only in turbid water but also the open ocean, seagrass is one of the most spatially suitable nature-based solutions. Highest suitability closest to the coast is observed in Mbweni, Kawe, Kivukoni and Kigamboni. In these areas, seagrass along the coast can help in reducing the wave energy that reaches the coastline. This not only reduces the potential for waves to erode the coastline, but also attenuates wave energy, lessening the strength with which storm surges could potentially reach the coast and damage infrastructure. Similar to coral reefs, due to its ability to grow in open waters, the open ocean has been identified as highly suitable. However, before accepting this conclusion, local conditions need to be assessed along with human activity in order to determine more spatially specific areas of potential expansion/implementation.

Similar to the suitability map for coral reefs, the suitability results for seagrass is also dominated by favourable areas. This is due to the fact that seagrass can flourish over large areas close to the coast, in areas of turbid water and in the open ocean; given depth and water temperature are appropriate. Since no water depth nor water temperature data was obtained for the suitability analysis, open water as a whole was marked as moderately suitable. It would therefore be necessary to conduct a local study in order to identify the extent to which the open ocean is legitimately suitable for seagrass to grow. What is important to consider are the highly suitable areas which are concentrated in close proximity to the coast where submerged vegetation already exists. The areas that are highly suitable and found in areas further from the coastline are around coastal islands, where submerged vegetation is once again already present.

6. Discussion

In Dar es Salaam's coastal districts, high rates of coastal erosion, flooding and infrastructure damage have been recorded. Being a low-lying coastal city, Dar es Salaam is naturally exposed to climatic factors such as storms, tides and changing sea-levels, all of which can be linked to the previously mentioned risks. In recent years, however, human-induced climate change has caused sea level rise, stronger storm surges and more frequent extreme weather events, which increase the severity of coastal erosion, flooding and infrastructure damage (Mimura, 2013). In response, a number of coastal adaptation measures have been implemented to reduce coastal vulnerability. The majority of these measures are classified as grey infrastructure such as seawalls and groynes. Despite these measures, studies have found that the coast of Dar es Salaam continues to experience heavy erosion, damaging floods and expensive damage to coastal infrastructure (Kiunsi, 2013; START, 2011; Watkiss et al., 2011). Future climate change will most likely exacerbate these risks (Kiunsi, 2013; START, 2011).

6.1 Nature-based solutions align to the integrated holistic benefits in the SETs framework

Adaptation measures are therefore an integral part of protecting Dar es Salaam. So far, coastal adaptation measures have been largely technical, grey solutions, which exclude socio-ecological functioning. As highlighted by the SETs framework (Fig. 1), grey infrastructure is expensive, and reliance is heavily placed on its success. In Dar es Salaam, seawalls and groynes inhibit sediment flow and can cause unwanted erosion further downstream (Prasetya, 2007). Furthermore, studies have shown that such measures become ineffective when sea-levels rise as their ability to reduce incoming storm surges is quickly reduced (Kallis, 2007; Depietri & McPhearson, 2017). The uncertainty and non-stationarity associated with climate change is not favourable for the limited benefits and functioning of seawalls and groynes.

This opens a window of opportunity for nature-based solutions, especially because some of the most common and effective nature-based solutions already naturally occur along the coast of Tanzania. When applied to the SETs framework, nature-based solutions fall within green infrastructure, which distribute the disproportionate reliance grey infrastructure has on technical factors among social and ecological factors too. Mangroves, seagrass, dunes and coral reefs rely primarily on natural ecosystem functioning. They also create and reinforce a number of ecosystem services which not only benefit ecosystems, but humans as well. These additional benefits, referred to as co-benefits are therefore ecological and social. Mangroves can be used as an illustration of these co-benefits. Mangroves are biodiversity hotspots which provide nesting grounds for species as well as a source of food for local communities, serving as provisioning and supporting ecosystem services, respectively. Mangroves can also filter water, reducing the amount of pollutants found in water and creating more suitable habitats for flora and fauna. Mangroves also trap flowing sediment and anchor existing sediment down, which can help limit rates of erosion. Filtering of pollutants and limiting coastal erosion are two important regulating ecosystem services. Coral reefs, seagrass and sand dunes similarly provide an array of provisioning, regulating cultural and supporting services which are beneficial to both humans and ecosystems.

In addition to these ecosystem services, or co-benefits, nature-based solutions are legitimately effective adaptation measures against climate impacts. The nature-based solutions discussed in this thesis are particularly effective for the specific threats faced in Dar es Salaam. All four nature-based solutions are able to greatly reduce incoming wave energy which can reduce flooding potential, erosive power and ability to damage infrastructure. An invaluable function of nature-based solutions is their dynamism. nature-based solutions have the ability to grow in response to sea-level rise. This is invaluable when creating an adaptation measure for something so uncertain as climate change.

6.2 A need for better research into site-specific contexts for assessing and applying nature-based solutions

The site-specific nature of this research offers insights into the specific demands for and application of locally relevant knowledge and criteria for determining the suitability of nature-based solutions. Among other things, this study reveals that several nature-based solutions may be applicable for a particular area (Fig. 4-7). From a methodological point of view, this lends support for the use of multi-criteria approaches in seeking solutions for complex environmental problems such as adaptation to climate change vulnerabilities. From a policy point of view, it reveals that local communities and policymakers seeking possibilities for adaptation measures have options from which the most appropriate, affordable, and locally sanctioned choices can be made. While suitable areas could be identified for each of the proposed solutions, it must be noted that there are a number of barriers to implementation which should be discussed.

Nature-based solutions are a relatively new and under-researched adaptation measure. For implementation to be possible in Dar es Salaam, policy support is required. Planning officials and decision-makers must see the benefits brought about by nature-based solutions and push for this method to be implemented over traditional grey solutions. This can be facilitated through further research and acknowledgement of the socio-ecological benefits highlighted by the SETs framework. Once nature-based solutions are implemented, additional regulations must be set to protect the green infrastructure. This is especially necessary with mangroves, which have been illegally deforested to profit off as a raw good. Destructive fishing methods and pollution also occurs along the coast of Dar es Salaam (Kebede & Nicholls, 2011). Although mangroves, seagrass and corals can increase biodiversity, which is important for the livelihoods of local communities that depend on activities such as fishing to sustain themselves, there needs to be regulations in order to ensure the responsible use and exploitation of such ecosystem services and co-benefits. Without such regulation, the sustainability of nature-based solutions and their benefits is uncertain. Urban development and poverty reduction policies need to be adjusted in order to integrate disaster risk management and climate change adaptation measures to take into consideration long-term effects of climate change (START, 2011). In terms of policies and regulations that already exist, there is a need for better enforcement (START, 2011).

6.3 Growing international recognition of nature-based solutions and implication for coastal adaptation initiatives

Nature-based solutions are becoming increasingly recognised in the climate change adaptation sector (UN Global Compact, 2019). The United Nations Climate Action Summit strongly supports the use of nature-based solutions in addressing the climate crisis (UN Global Compact, 2019). The Summit calls on all companies to further support the development of nature-based solutions as a form of climate mitigation, resilience and adaptation (UN Global Compact, 2019). The use of nature-based solutions for climate mitigation, resilience and adaptation is supported and promoted by the UN Environment Programme, who compiled a compendium of proposals of ways in which the implementation of nature-based solutions can be made more effective (UNEP, 2019). The IUCN recognises the crucial role nature can play in addressing climate change and the combined benefits at environmental, social and economic levels (IUCN

France, 2016). In doing so however, they identify various knowledge gaps associated with nature-based solutions (Rizvi & van Riel, 2018).

The IUCN states that there is a crucial knowledge gap concerning the tools and methods for implementing different nature-based adaptation approaches and evaluating the impact of such strategies (Rizvi & van Riel, 2018). There is a specific need for “an integrated tool or toolbox that addresses both communities’ vulnerabilities and those faced by local biodiversity and ecosystems” (Rizvi & van Riel, 2018). This thesis addresses this important gap by applying existing tools and methods to a specific case study and highlighting the main vulnerabilities faced due to climate change impacts, evaluating the potential use of nature-based solutions and contributing to knowledge by conducting a suitability analysis of nature-based solutions in an area that is recognised to lack in research.

6.4 Linkages to Sustainability Science

The results of this thesis present a valuable opportunity for considering nature-based solutions within the greater context of sustainability science, urban sustainability and climate change adaptation. This thesis is linked to sustainability science as it highlights the interactions between climate change, ecology (as an adaptation measures) and the associated societal benefits. The effects of climate change have been and will continue to affect the interactions between humans and nature. The use of nature-based solutions as a form of climate change adaptation and mitigation brings nature and ecosystem services into the forefront by showing their potential to not only benefit ecosystems but provide significant protection to human lives, infrastructure and the economy. Making use of nature as a defence mechanism is not only cheaper than traditional methods but also requires less maintenance and has in many cases proven to be more dynamic and effective. Widespread adoption of nature-based solutions for climate change adaptation can, with effective management, ensure the protection and improve livelihood possibilities for current and future generations.

The use of nature-based solutions as a climate change adaptation measure has positive implications for urban resilience. Urban resilience measures the ability of urban systems to maintain continuity though shocks and stresses while adapting and transforming towards sustainability. Nature-based solutions increase the adaptive capacity of urban centres especially in terms of climate change impacts. They also support a shift towards a sustainability transformation by increasing ecological functioning and bringing ecosystem services into cities. Along coastal regions such as Dar es Salaam, urban resilience is very important due to the exposure developing coastal cities have in terms of climate change impacts.

The use of nature-based solutions falls within the goals of the UN Sustainable Development Goals (SDGs). Nature-based solutions promote the sustainable use of nature in order to protect and benefit humans and ecosystems (Kalantari et al., 2018). Nature-based solutions can increase biodiversity and reverse land degradation, which is in line with SDG 15 (life on land). Nature-based solutions also reduce climate change impacts through adaptation and mitigation, relating to SDG 13 (climate action). It can also be argued that nature-based solutions strengthen the ability to implement and restore the partnership for sustainable development (SDG 17). Nature-based solutions can strengthen partnerships between governments, scientists and local communities who benefit and have a responsibility to ensure the maintenance of such measures. Furthermore, when applied to urban areas, nature-based solutions promote sustainability and climate resilience in cities (SDG 11). The co-benefits related to nature-based solutions increase food security, especially for local communities as well as support economic growth (SDG 2 & 8).

7. Conclusions & Future Research

There is a window of opportunity to use nature-based solutions as climate change adaptation measures along the coast of Dar es Salaam. Nature-based solutions can not only protect the coast from vulnerabilities associated with climate change specific to the context of Dar es Salaam but would also bring about co-benefits which would be positive for local people and the economy.

Limited research has been conducted on the vulnerabilities associated with climate change in Dar es Salaam and possible adaptation measures. Even less research exists on the potential of using nature-based solutions as an alternative adaptation strategy. This thesis provides an overview of the vulnerabilities associated with climate change in Dar es Salaam and assesses the potential for using nature-based solutions. A spatial analysis is also conducted to identify potential areas of implementation. Although this thesis addresses several gaps in the literature, additional research is required.

Further research should be conducted on the benefits of using nature-based solutions over traditional grey infrastructure especially in vulnerable coastal areas. Research on the role of nature-based solutions in mitigating hazards should also be expanded. There also lacks evidence of the direct effects of nature-based solutions on human well-being, which may explain the lack of nature-based solutions as a common adaptation measure. However, as highlighted throughout this thesis, nature-based solutions have the potential to be inexpensive, low-maintenance and effective climate change adaptation measures which benefit socio-economic and ecological systems.

8. References

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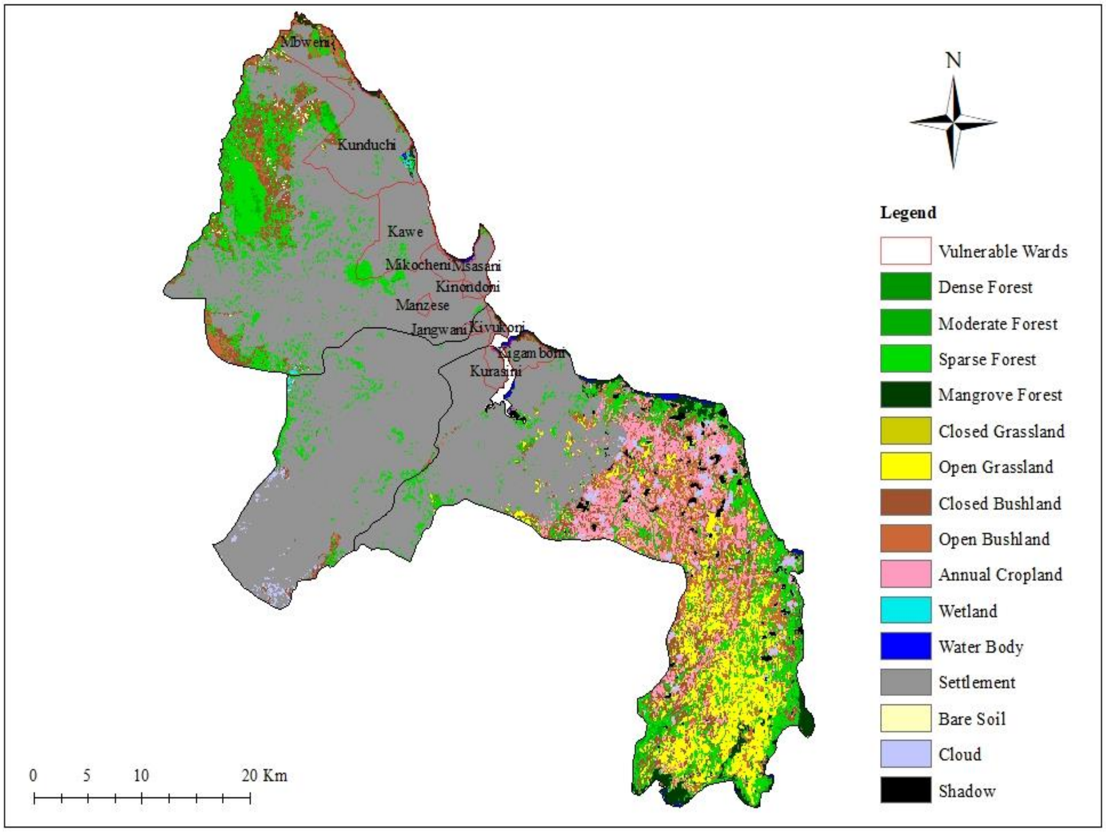
9. Appendices

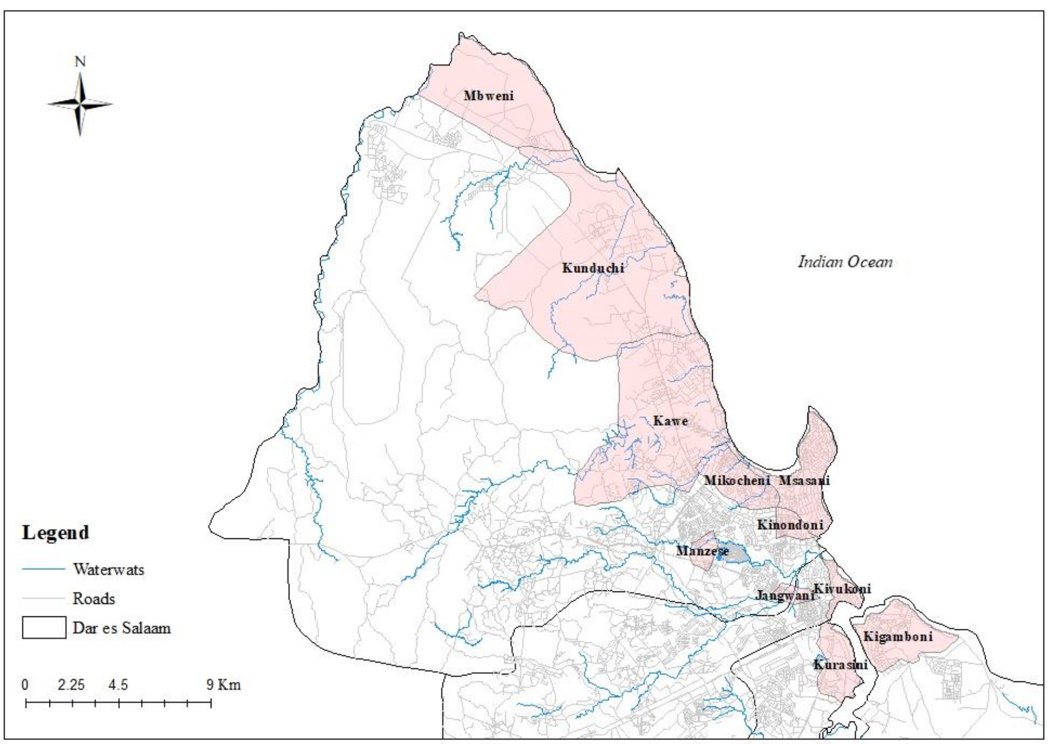
Appendix A. Overview of additional GIS data to create supporting maps.

File Name	**File Type**	**Source**	**Description**
High Resolution Settlement Layer	Vector	CIESIN (2016)	Settlements
Tanzania Geomorphology: Landform and Lithology	Vector	Harvard (2003)	Geomorphology

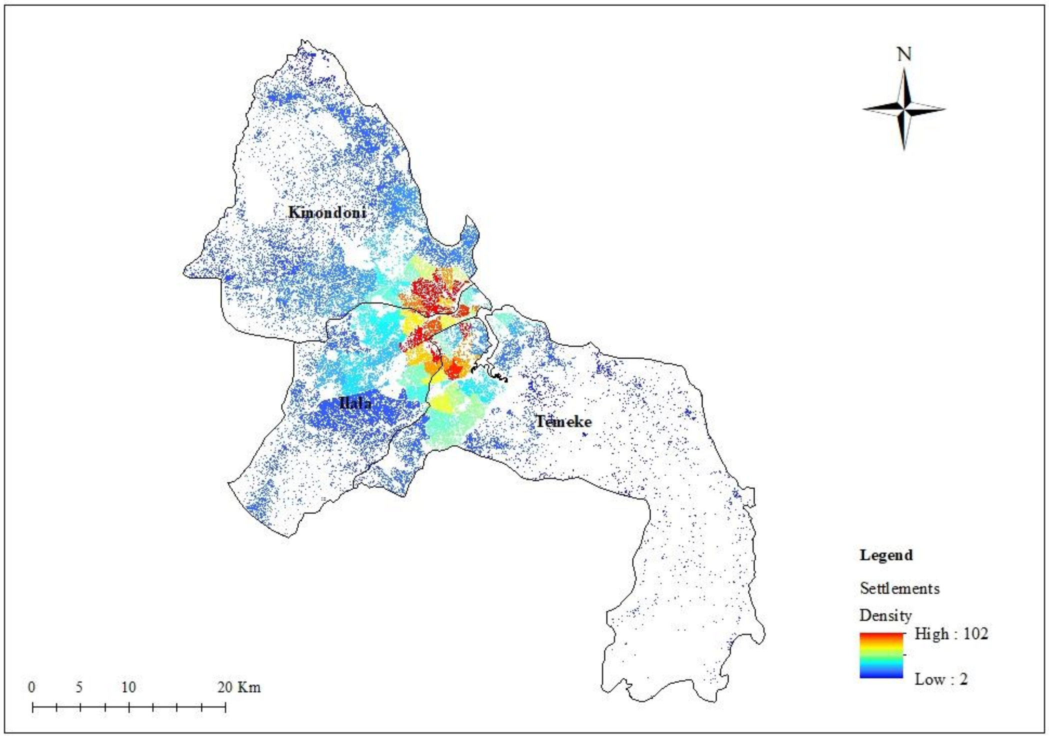
Appendix B. Land cover of Dar es Salaam overlaid with the vulnerable wards.



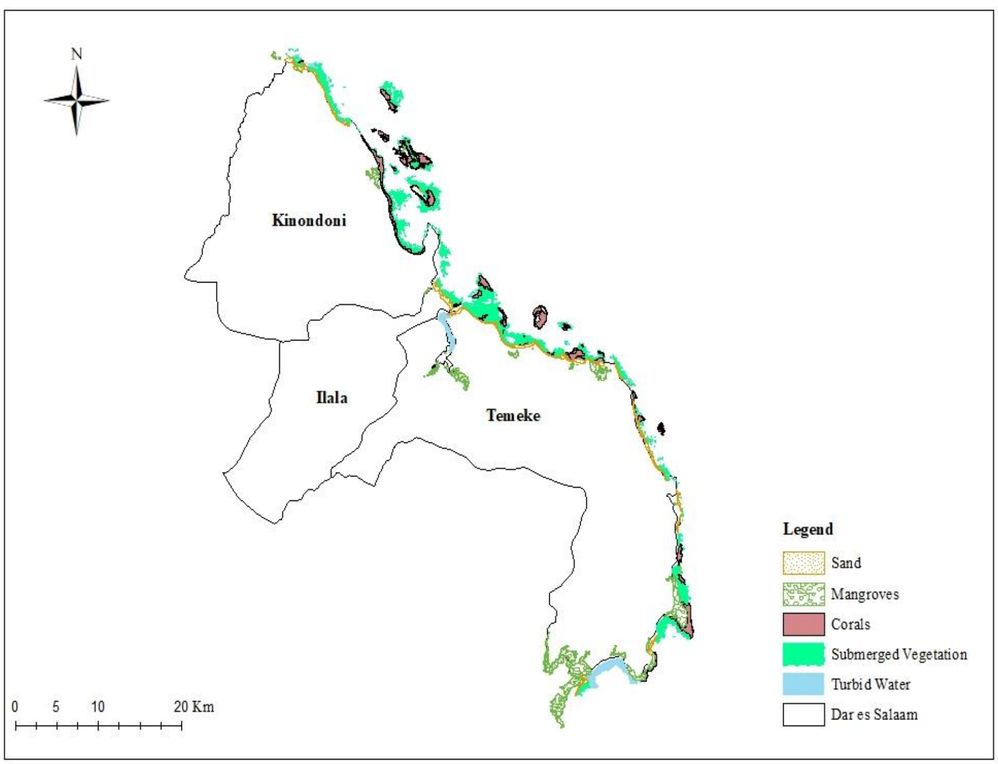
Appendix C. Major roads and waterways of Dar es Salaam overlaid with vulnerable wards.



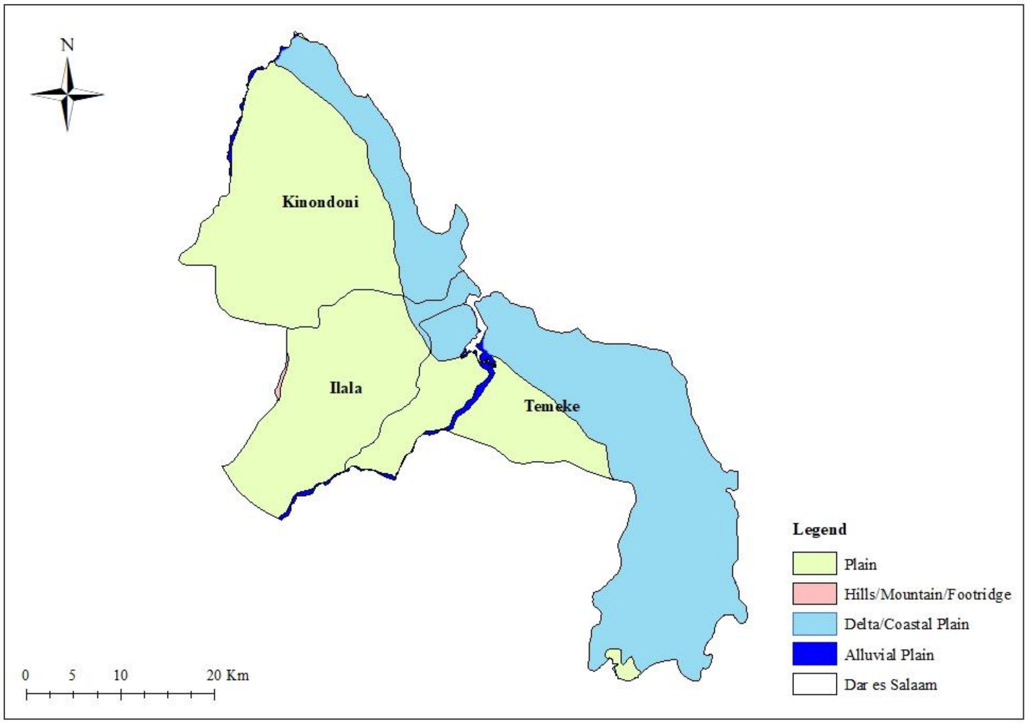
Appendix D. Concentration of settlements in Dar es Salaam.



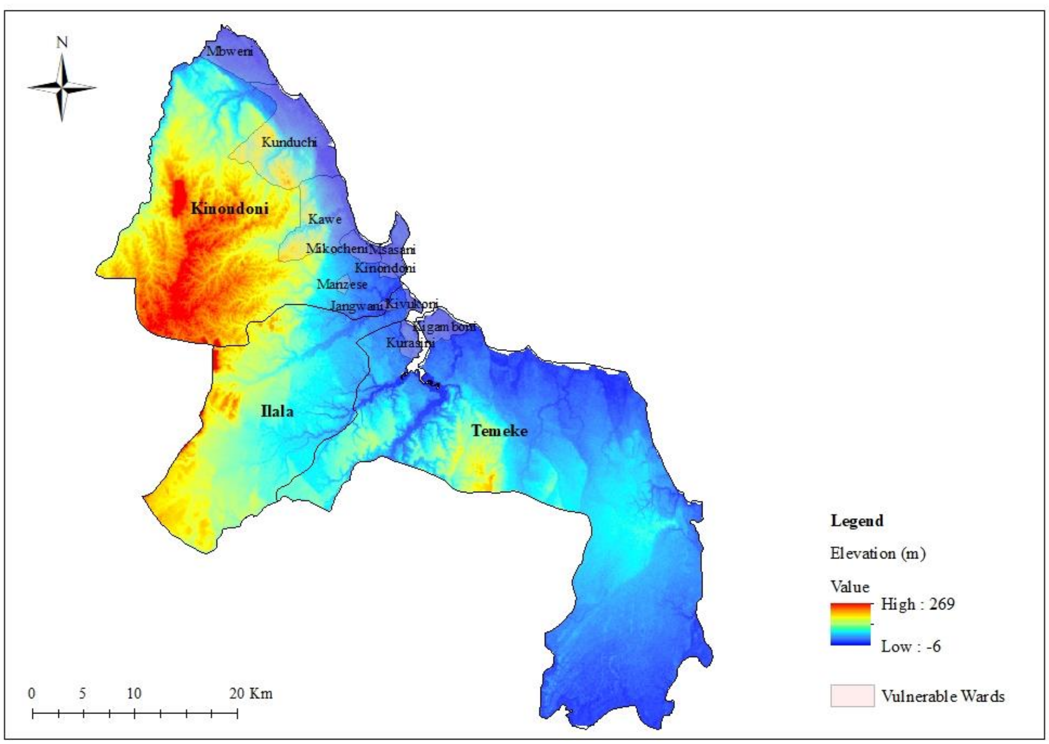
Appendix E. Overview of coastal vegetation along the coast of Dar es Salaam.



Appendix F. Geomorphology of Dar es Salaam.



Appendix G. Digital elevation model (DEM) of Dar es Salaam overlaid with vulnerable wards.



Appendix H. Survey questions from key-informant interview.

1. Which of the following climate-change related factors pose the largest risk to the coast of Dar es Salaam? (Please rank in terms of the severity of the threat)

2. What specific areas along the coast of Dar es Salaam are most vulnerable to threats from climate change? (Please provide the name of the area and the threat(s) faced)

3. What makes each of the previously identified areas vulnerable to such threats? (i.e. high rates of coastal erosion, high concentration of unplanned settlements, lack of adaptation measures)

4. What measures have been taken along the coast of Dar es Salaam to mitigate vulnerabilities to climate change (i.e. installation of groynes, seawalls, rehabilitation of coastal forests, etc.)?

5. To what extent have nature-based solutions (such as use of mangroves, sea grass, reefs) been considered as possible adaptation measures (in climate adaptation plans, policies, projects, etc.)?

6. In what ways can nature-based solutions benefit Dar es Salaam socially and economically?

7. Are there any drawbacks to using nature-based solutions instead of "hard measures" (i.e. sea walls, groynes)?

8. Are there any political or economic challenges associated with nature-based solutions in Dar es Salaam? If so, what type?