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The Possibilities of Capturing Rainwater and Reducing the Impact of Floods: A Proposal for the City of Beira, Mozambique

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Abstract: Modern societies face various challenges, including climate change, rapid urbanization, and sometimes inadequate urban planning policies. In recent years, extreme weather events have received increasing attention for their impacts on cities, humans, and ecosystems worldwide, particularly on coastal towns in Mozambique, such as cyclones, floods, water pollution, and water scarcity, demonstrating their vulnerability to climate change. Cities must adapt to cope with the pressure on their water resources, and it is essential to ensure that communities have access to safe, reliable, and affordable water. A viable way to promote this resilience and simultaneously reduce costs in domestic budgets is to use rainwater to meet daily needs where water quality parameters are not required for consumption. According to the results of this study, it is possible to significantly reduce potable water use from the municipal water supply network by harvesting rainwater, up to 40% when the use does not require potable water at all, proactively protecting this vital resource. In addition to these direct benefits, the large-scale deployment of rainwater harvesting (RWH) systems in densely urbanized areas can also provide indirect benefits, such as reducing peak flow volumes in stormwater drainage systems and potentially reducing the frequency of urban floods. These benefits result from the reduction in the volume and duration of water sent to the drainage network, which can help to improve the overall resilience of communities in the face of climate change and other challenges.

Keywords: climate change; sustainable development; urban water management; water stress; rainwater harvesting; stormwater capture efficiency; water supply system

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1. Introduction

Modern societies are facing numerous challenges [1], including extreme weather events that have significant impacts on cities, humans, and ecosystems. These events can lead to the depletion of natural resources, disruption of food, water, and energy supplies [2], negative welfare effects, and an increased risk of urban areas being affected by natural disasters and climate change [3]. Poorly adapted drainage systems can exacerbate flood risk in urban areas, but proper urban stormwater management can help reduce this risk [4].

By 2050, it is estimated that the potential loss due to flooding could reach $1 trillion as a result of rapidly increasing anthropogenic activities and extreme weather events, of which flash floods have a high mortality rate [5,6]. According to Paramita Roy et al. [7], different factors that contribute to flooding, such as heavy rainfall, storm flow, and poorly maintained infrastructure, are linked to climate change. These factors combine to create a range of hydrological, meteorological, geomorphological, and structural failures that lead to flooding.

More recent studies have shown that human interference in the natural environment through urbanization, erosion, and encroachment of riverbanks into human structures has resulted in the decreasing connectivity of floodplains with streams and an increased incidence of flooding over an extended period [8].

Temperature and precipitation during the growing season play a crucial role in the health of all living systems, particularly plants, which are particularly sensitive to changing weather conditions at this time [9]. It is expected that the frequency of composite hot and dry events will increase in the near future, approximately four times that of 1950–1980 [10,11]. This may lead to water shortages for human consumption, tree mortality, and crop loss during periods of drought and hot weather, posing threats to agricultural production, food security, and wildfires [11,12].

As a result of various factors, water availability in many parts of the world has been less predictable, and increasing flooding events threaten to destroy water points and sanitation facilities, contaminating water sources [13].

The current state of water resources highlights the need for improved management. It is necessary to recognize [14], measure, and express the value of water and incorporate it into decision making, which is key to achieving sustainable and equitable management of water resources and meeting the United Nations Sustainable Development Goals (SDGs) for 2030 [15].

By promoting sustainable consumption patterns to mitigate and adapt to the "accelerated and equitable" impacts of climate change [16], the UN Sustainable Development Goals (especially Goals 6, 11, and 12) aim to improve access to safe water and resource efficiency in water systems [17]. Goal 6.4 proposes, "From now until 2030, significantly increase the efficient use of water resources in all sectors and ensure the sustainability of freshwater extraction and supply to address water scarcity and considerably reduce the number of people suffering from water shortages" [18].

Following FAO [19], the gradual increase in global water stress over the last 20 years reflects increasing stress in several regions. Freshwater resources are in danger of deteriorating in terms of quality and quantity (eutrophication, contamination of organic matter, salt intrusion), which makes this issue one of the most severe threats to sustainable development [20].

In Ghana, Mozambique, and Zimbabwe, future water shortages could increase the risk to sick people because families often store precious resources indoors, creating breeding grounds for mosquitoes carrying diseases. Water is also necessary for basic sanitation facilities to prevent bacteria, viruses, and parasites from contaminating freshwater, which increases the risk of cholera and typhoid fever [21]. The population of Africa and Mozambique, in particular, is expected to double between 2016 and 2050 (Figure 1), with 80 percent of new residents living in urban areas. Therefore, African city leaders must build and promote urban water resilience, whereby communities have sufficient access to safe, reliable, and affordable drinking water to survive and thrive within a resilient, sustainable, and adaptive urban water system [22,23].

The centralized infrastructure of water systems worldwide, such as pipelines, treatment plants, and drainage networks, puts pressure on these systems [24]. To provide adequate water services, cities should move away from traditional water services and toward hybrid solutions that combine centralized and decentralized technologies. These solutions are based on new principles for infrastructure design, making them highly adaptable to changing conditions since they incorporate flexible features at various scales [25]. As reservoirs of resources and producers of secondary resources, cities are crucial to the circular economy [26]. Urbanization can reduce its impact by capturing urban resources and strengthening city resilience. Resilience refers to the ability of a system to adapt to changing conditions and remain stable [27].

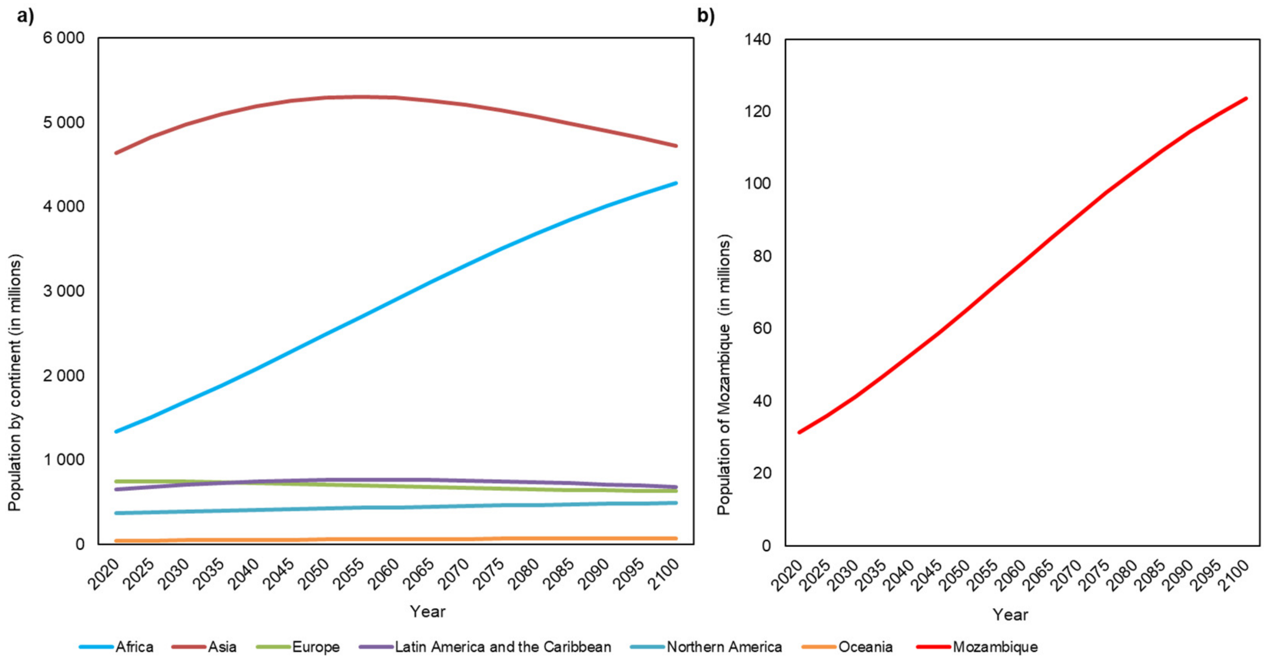


Figure 1. Probabilistic Population Projections based on the World Population Prospects 2019, between the years 2020 and 2100, by continent (**a**) and for Mozambique (**b**) [28].

Governance reform is necessary to establish adaptive and resilient management of urban water resources, considering the complexity, uncertainty, and immediate and long-term changes [29]. The study of nature-based solutions, which is closely related to other concepts such as the ecosystem approach [30,31], has been utilized by scientists since the early 2000s [3,32].

A robust multidisciplinary understanding of the value added to urban spaces and the provision of multifunctional spaces is necessary for effective water management within urban environments. The benefits of urban water bodies range from providing water, habitat, and energy to eliminating pollutants, providing convenience, and providing recreational opportunities [33]. Historically, water management within urban spaces has been performed separately from other urban functions and spatial requirements [34].

There are two main types of rainwater collection systems: total flow systems and diverter systems. Total flow systems, also known as first flush systems, capture the roof runoff and store it in a tank. The water is filtered or screened to remove larger particles before being stored in the tank. Any excess water is directed to the drainage system when the tank is full. These systems are effective at capturing and storing a large volume of water, but they can be less efficient in areas with frequent, heavy rain because they may not store all the water that falls on the roof. On the other hand, diverter systems separate a portion of the roof runoff from the total flow and divert it to the sewerage system. The remaining water is directed to a storage tank. These systems are more efficient in areas with frequent, heavy rain, as they allow excess water to be directed to the sewerage system rather than stored in the tank. However, they can be less efficient in areas with low precipitation rates, as the efficiency ratio decreases with decreasing flow. In addition, the fine mesh sieves used in these systems can become clogged over time, reducing their overall efficiency [35].

There are many examples of cities that have implemented rainwater harvesting (RWH) practices and are often referred to as "Sponge Cities." For example, Singapore has made significant efforts towards becoming a "City in a Garden" through the implementation of RWH systems in public and private buildings, as well as in green spaces and public parks [36]. Melbourne, Australia, has also implemented RWH practices, including green roofs, permeable pavements, and detention basins to capture and reuse rainwater [37,38]. Curitiba, Brazil, has implemented RWH practices as part of its efforts to become more sustainable and resilient, with systems in public buildings, green spaces, and public parks [39,40]. Suwon, South Korea, has implemented RWH practices such as green roofs, permeable pavements, and detention basins, as well as education and outreach programs to promote RWH [41].

This study aims to evaluate the potential contribution of capturing rainwater on total available water resources, as well as the ways in which it can reduce the impact of floods, particularly in the city of Beira, Mozambique. The research will involve analyzing data to examine the specific patterns and characteristics of RWH in Beira.

This research aims to mitigate the effects of accelerated urban development on natural ecosystems in the city of Beira, and other cities facing similar challenges. Beira has experienced several natural disasters, such as Cyclone IDAI [42], and is facing issues related to stormwater and water supply. The implementation of Sponge City technologies, such as green roofs, green spaces, artificial ecological stormwater zones, infiltration ponds, biological preservation facilities, and water-permeable pavements [4], can help address these urban problems while simultaneously protecting the environment.

2. Materials and Methods

The use of rainwater collection has increased in many cities to reduce pressure on water supplies, mitigate floods, and address other vulnerabilities related to climate change [43]. In response to water scarcity and uncertainty about future water supplies, governments are reevaluating their water management models [29].

As urban populations continue to grow and water stress is exacerbated by climate change, there is a need for innovation in urban water supply systems. Technologies such as modular water treatment, complex systems analyses, and efforts to reduce energy and environmental footprints offer new opportunities for building resilient and secure water supplies. The following research was conducted in this study to optimize water supply systems and develop sustainable alternative water sources: (i) a literature review and data collection from public entities as well as the company (FIPAG) responsible for Beira's water supply; (ii) a survey of precipitation data in Beira; (iii) a study of the volume of rainwater captured by roof surfaces for household use and flood prevention; (iv) a study of transport systems; and (v) a study of storage systems.

2.1. Case Study Building: Beira

With a population of 533,825, Mozambique's fourth largest city, Beira, is subject to significant climate change. Its urban structure consists of neighborhoods connected by diagonals and reticulated meshes. There is an increasing need for a potable water and sewage system in the city, and a portion of Beira is affected by coastal erosion in addition to being built on flat, swampy terrain and extremely impermeable soil [44].

City of Beira is characterized by its vulnerability to flooding, and was severely impacted by tropical cyclone Idai, one of the most devastating storms in recent years, which made landfall as a category 4 storm on March 14, 2019, causing massive damage due to strong winds and flooding (Figure 2).

By choosing a building that is representative of the characteristics of the buildings in the neighborhood, this study can be more confidently extended to the larger population, providing more reliable and relevant results. In this case, the chosen building was specifically selected based on an urban characterization study in order to ensure that it accurately represents the characteristics of the buildings in the neighborhood under study. This allows the results of this study to be more accurately generalized to the larger population of buildings in the neighborhood.

The building "Casa Maria Noronha" was selected as a reference for this study based on an urban characterization study in "Building and Urban Characteristics for the Development of Intervention Strategies in the Ponte Gêa Neighborhood of Beira" [45]. It is a building located in the Ponte Gêa neighborhood and was designed by Portuguese architect Paulo Melo Sampaio in 1961. It features reinforced concrete structures, brick masonry walls, and sloped fiber–cement sheet roofs. It is apparently influenced by modern architecture, which was prevalent in the city from 1966 to the beginning of the 1970s.

Figure 2. The extent of standing water 19 March 2019 in the City of Beira (Adapted from [46]).

This study was conducted in the Ponte Gêa neighborhood (Figure 3), which is primarily residential and consists of multifamily buildings arranged in a well-defined urban structure with well-defined blocks. Additionally, in Appendix A (Figure A1), you can see the block where the building selected as a reference in this study is inserted.

Figure 3. Location of the building in the Ponte Gêa Neighborhood in the City of Beira.

In residential buildings, the water consumption of occupants is influenced by factors such as their characteristics and the efficiency of their housing [47].

2.2. Current Capture and Fueling System

The water that supplies the city of Beira is approximately 60 km from a water supply system with nominal capacities of capture, production, and storage of 60,000 m^3/d, 50,000 m^3/d, and 36,950 m^3, respectively. In addition to serving the municipality of Beira, it also supplies the municipality of Dondo and the administrative post of Mafambisse (Figure 4).

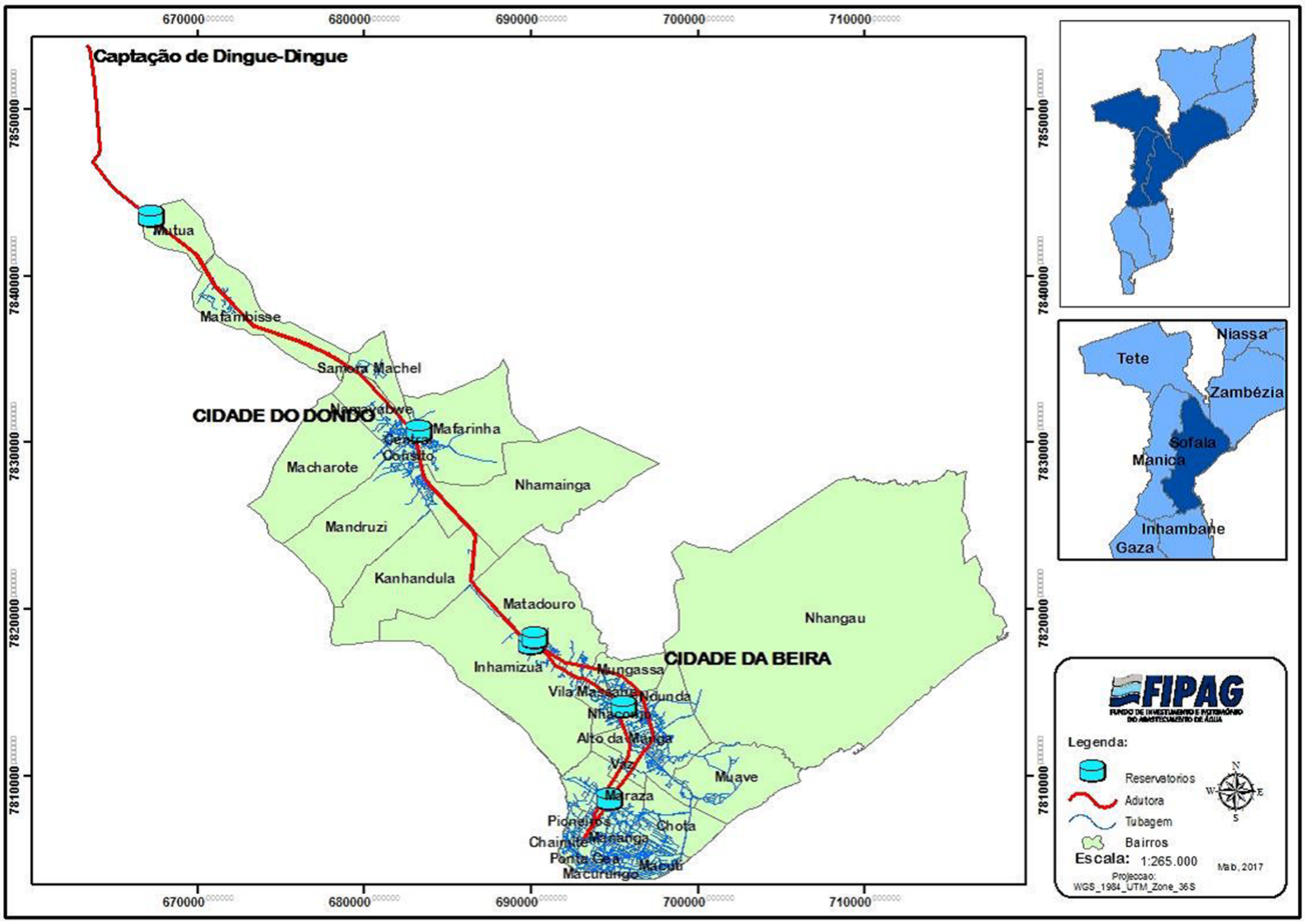


Figure 4. Water collection, storage, and distribution network for the City of Beira.

The municipal water supply is sourced from the surface or accumulated water of the "Pungué" River, which is treated at the "Mutua" treatment plant. The raw water from the "Pungué" River is channeled into a reservoir and then pumped through a collection of 3+1 submersible pumping functional groups with a nominal capacity of 1350 m^3/h. The water is then distributed through a network of over 942 km of primary, secondary, and tertiary pipes. However, due to the city's growing population, there is an increasing demand for new sources of water supply. Individual rainwater harvesting systems may be one option to help meet this demand and mitigate water crises in the region. Individual rainwater harvesting (RWH) systems can be an option to mitigate water crises in Mozambique, as well as in other neighboring African countries such as South Africa, Malawi, Zimbabwe, and Tanzania.

2.3. Precipitation Data

From 1991 to 2020, the National Institute of Meteorology of Mozambique provided rainfall records for the International Airport of Beira (Table S1 in supplementary materials). Annual precipitation during the modeling period is presented in Figure 5.

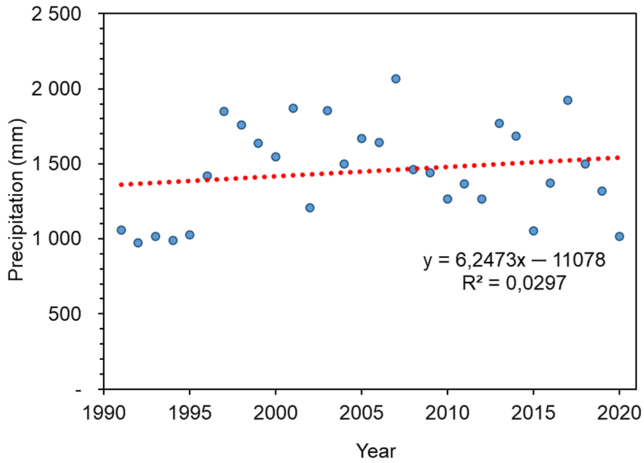


Figure 5. Hydrologic characterization between 1991 and 2020 for the city of Beira.

After collecting daily precipitation data for each month during this period, the total precipitation for each month was added, and the monthly average value between 1991 and 2020 was determined (Figure 6). The same process was repeated to determine the average number of days of monthly precipitation.

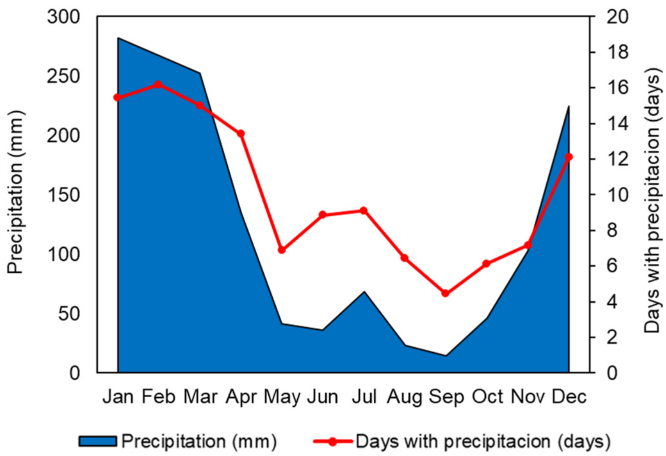


Figure 6. Rainfall pattern between 1991 and 2020 for the city of Beira.

Subsequently, a dynamic simulation of the rainfall data was performed using Meteonorm 8 software [48] to obtain climatic data for the horizon of 2100. Meteonorm is a software tool that allows users to access and analyze historical and forecasted meteorological data for various locations around the world. Interpolated long-term monthly averages were used to generate results stochastically for typical years. These results do not represent a current historic year, but rather a hypothetical year representative of what a typical year would look like at the selected location in the future.

The resulting monthly rainfall values were then used to investigate the effects of future climate change on the control of stormwater volumes and the water-saving performance of the Beira RWH system (RWH). To determine the water-saving efficiency, reliability, and stormwater harvesting efficiency of RWH systems, a water balance model was developed.

2.4. Collected Water, Transport, Storage, and Distribution

The RWH system was designed in accordance with ANQIP's ETA 0701 (version 10), dated 1 September 2021 to 19 January 2026 [49]. The ANQIP technical specification establishes technical requirements for the design, dimensioning, installation, certification, and maintenance of RWH systems in buildings for purposes other than human consumption. The first rainwater captured in each rainstorm (first flush) is recommended to be diverted from the system in order to reduce sediment in the deposits and for quality reasons. A minimum of 2 mm of rainwater is required to be diverted, according to Equation (1), during periods without precipitation.

$$V_d = R.A \quad (1)$$

where,

V_d—Volume to be diverted (liters);

R—Precipitation height to be diverted (mm);

A—Capture area (m^2).

The expression can determine the volume of rainwater used in a given period, as determined by Equation (2).

$$V_a = C.P.A.\eta f \quad (2)$$

where,

V_a—Monthly volume of usable rainwater (liters);

C—Flow coefficient;

P—Accumulated precipitation height in the period considered (mm);

A—Capture area (m^2);

ηf—Hydraulic filtration efficiency.

The expression that can determine the final volume of rainwater used is given by Equation (3).

$$V_{arec} = V_a - V_d \quad (3)$$

where:

V_{arec}—Rectification volume of usable rainwater (liters);

V_a—Monthly volume of usable rainwater (liters);

V_d—Volume to be diverted (liters).

Water is collected from roofs and patios during rainfall events and stored in tanks or cisterns to meet internal and external needs [50]. By installing RWH systems, water can be saved, and pressure on urban water supplies can be relieved [47], promoting the concept of a Sponge City [50] and increasing urban system resilience. Harvested rainwater can be used to replace tap water for non-drinking or drinking purposes [51].

3. Results

There is currently a centralized water treatment system in place for the distribution of urban water. Freshwater is generally treated as potable before being distributed by these systems.

However, optimal and sustainable water distribution remains challenging, especially as water networks age, where pressure management is essential to prevent leaks and breaks [52]. To reduce overall energy consumption without compromising performance, collection areas at the building, block, and neighborhood levels (along with individual and community strategies) are an effective means to do so.

3.1. Precipitation

The city of Beira, Mozambique, experiences a tropical savannah climate with rainfall peaking from December to March [53]. Using rainfall records from 1991 to 2020, it has been determined that Beira has a seasonal precipitation pattern. The hydrological year begins in November, and the rainy season lasts for six months (November to April), followed by six dry months (May to October). On a daily scale, it is evident that the rainy season is characterized by several days or weeks without precipitation, despite substantial overall rainfall.

According to the precipitation data (Figure 6 and Table S1), which represent the hydrological characterization of Beira City between 1991 and 2020, a linear trend was determined until 2100 (Figure 7a), predicting an approximate precipitation of 2041 mm for 2100. In Figure 7b, the simulation of precipitation for 2100 in Meteonorm is represented, showing an increase in precipitation during the rainy season up to 400 mm. However, there is a reduction in the number of rainy days during the dry months.

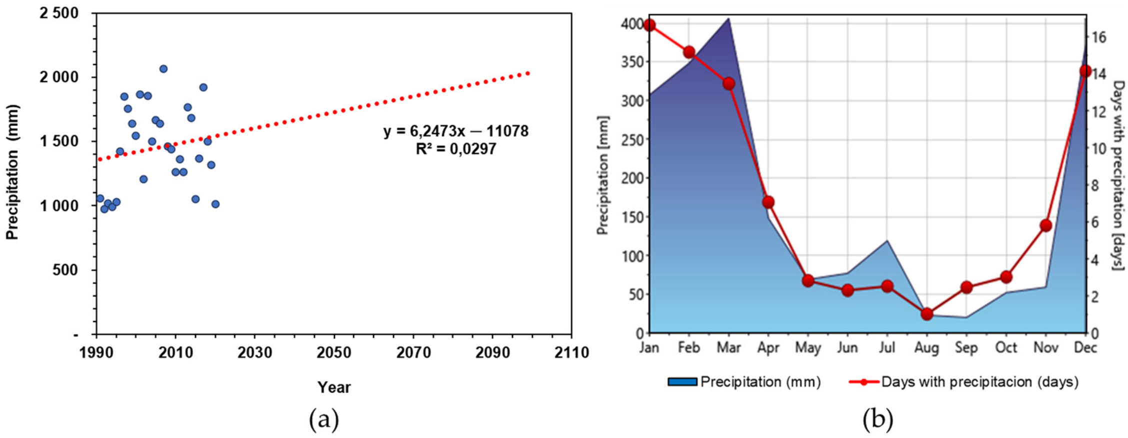


Figure 7. Hydrological characterization between 1991 and 2020 for Beira City, linear trend until 2100 (**a**), and simulated precipitation pattern for 2100 (**b**).

The results of the hydrological characterization can be used to inform decision making related to water management, flood risk assessment, and other applications.

On the other hand, it is important to remember that rainwater, due to its composition, performs better for many household purposes and is more suitable than drinking water [51,54]; for example, it does not contain minerals, so after drying, it does not leave white stains, making it suitable for cleaning windows or washing car bodies. It also does not contain aggressive chlorine, making it suitable for watering houseplants and gardens. Additionally, it does not form limescale, which is advantageous in many ways and does not cause osmosis. This makes it suitable for use in laundry, floor washing, and cleaning.

3.2. Rainwater Harvesting

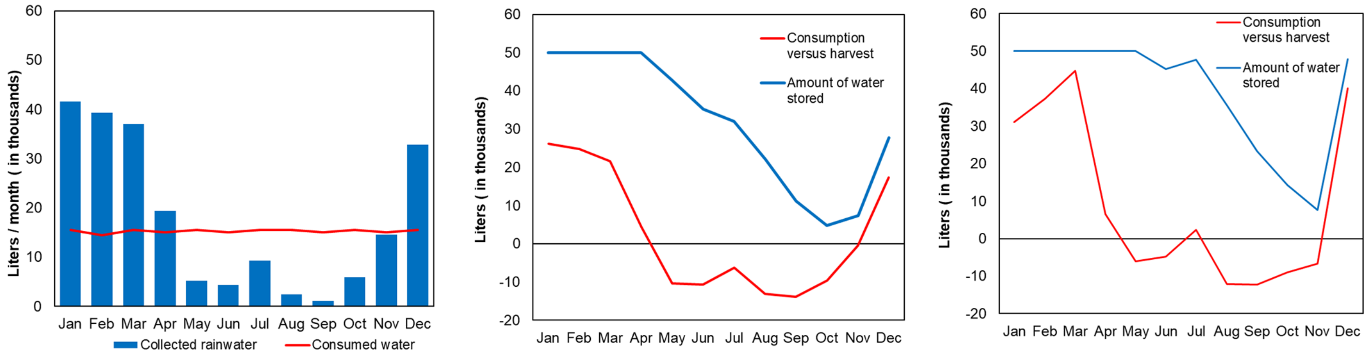
The monthly volume of usable rainwater was calculated considering the average rainfall data from 1991 to 2020 (Table 1) and correction for the initial runoff and subsequent water filtration deviation. In the analysis of the precipitation data, it was evident that there were several days without precipitation, even during the rainy season.

Table 1. The monthly volume of usable rainwater.

Title 1	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
C	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
P (mm)	282.1	267.2	252.1	135.3	41.3	35.9	68.2	23.3	14.4	46.2	103.0	224.4
A (m^2)	210	210	210	210	210	210	210	210	210	210	210	210
ηf	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
V_a (liters)	42,657	40,405	38,112	20,464	6248	5432	10,308	3522	2180	6989	15,580	33,931
V_d (liters)	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050	1050
V_{arec} (liters)	41,607	39,355	37,062	19,414	5198	4382	9258	2472	1130	5939	14,530	32,881

Rainwater was used exclusively for non-potable purposes in this study, such as for flushing toilets and washing clothes [47]. It is estimated that the total water consumption in Draft Regulation of Public Water Distribution and Wastewater Drainage Systems in Mozambique is 125 liters per person per day [55] in areas with more than 2000 inhabitants with a home supply and building distribution, and rainwater can supply 40% of their water needs. Using rainwater, a non-potable consumption rate of 50 liters per person per day was adopted and considered constant. Based on the fact that the building under study consists of two fractions, each with three bedrooms, a living room, a kitchen, a bathroom, and a storage room, containing two families of five people per fraction, we consumed approximately 500 liters per day.

Figure 8a shows the amount of rainwater collected and consumed, demonstrating the need to store water during the rainy season for use during the dry season.



(a) (b) (c)

Figure 8. Collected rainwater versus consumed water (designed for 1991–2020) (**a**), the amount of water stored versus consumption (**b**) (designed for 1991–2020), and the amount of water stored versus consumption (simulated precipitation pattern for 2100) (**c**).

The analysis of the previous graph illustrates the need for water storage during months of low rainfall. Rainwater harvesting (RWH) is lower than consumption from May to October. To maximize the system's efficiency, we suggest installing a tank with a capacity of 50,000 liters, which would allow for the storage of up to 20% more of the maximum Varec volume determined in January, which reaches its maximum capacity at the end of the rainy season (April). This would ensure a supply of non-potable water during the dry season when precipitation is low. Figure 8b shows the monthly amount of water stored and consumed after the harvest.

To sustainably meet future water-saving and stormwater control requirements in changing climatic conditions, it may be necessary to adjust the tank size, catchment areas, and water demand rates. Decentralized rainwater reuse facilities could also help reduce the energy and transportation requirements associated with water distribution, reducing water stress. Our proposed collection, storage, and consumption system can potentially reduce drinking water consumption from the supply network by approximately 40%, or about 183,000 liters annually, for the building type under study. According to the simulations for 2100 (Figure 8c), an increase in precipitation is expected, which would increase the rainwater harvesting capacity and stimulate the development of community systems.

It is worth noting that the proposed system not only reduces the demand on the public water supply but can also accommodate the discharge of large volumes of water during periods of heavy rainfall. This would help to alleviate the pressure on existing infrastructure, which may already have limited capacity. For example, suppose we consider the block where the building under study is located (Figure A1 in Appendix A). In that case, it is verified that all the buildings inserted in this block have similar geometric characteristics and use, so if we use the surface of all the roofs for the capture of rainwater, which corresponds to 3200 m^2, it is estimated that approximately 3,441,212 liters of water could be collected annually for non-potable consumption while reducing the peak discharge in the existing infrastructure. Furthermore, although the number of rainy days is expected to decrease, precipitation intensity is expected to increase.

4. Discussion

Local precipitation is one of the main variables of interest in system design and evaluation, as it determines the amount of collectible rainwater generated from a given contributing watershed, in this case, the covers [56]. It should be noted that rainwater is relatively free of impurities when it is produced in the atmosphere as rain. However, various factors can contribute to the presence of pollutants or contaminants in rainwater, such as the absorption of chemical products (atmospheric pollution) transported through the air during rainfall, exposed surface materials that can capture pollutants, debris, and dust on the surfaces of catchment areas, and the storage and use of rainwater [57].

Although filtration can effectively eliminate bacteria, it does not guarantee the safety of drinking water. Therefore, it is important to use this resource sustainably and efficiently [58]. As shown in Figure 9, a rainwater harvesting (RWH) system is an environmentally friendly and simple method for collecting, filtering, and storing rainwater inside and outside a building. Sand filters, which are one of the most common and inexpensive water treatment systems, have been used since 1804 [59]. These filters can be constructed using gravel, sand, and activated carbon in conjunction with a polyester geotextile membrane. Polyester blankets can also be used as filter beds as a low-cost alternative [60].

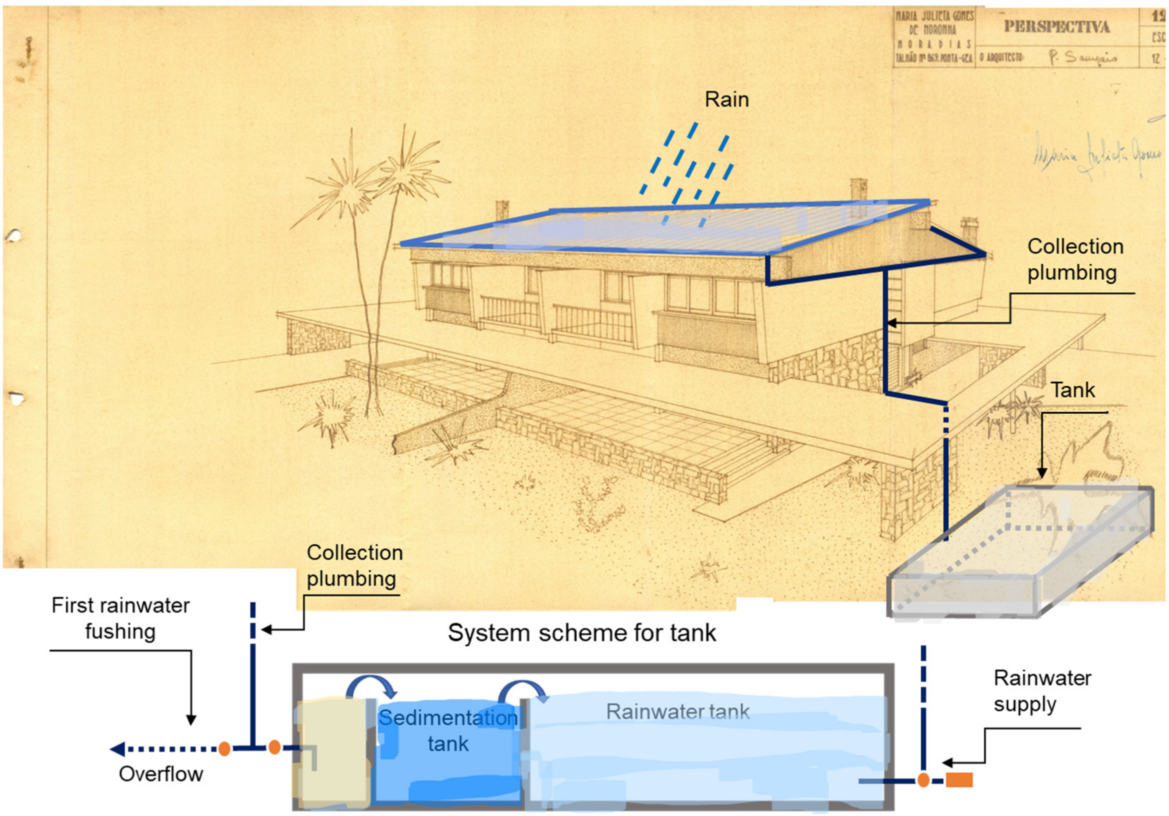


Figure 9. System scheme for rainwater harvest.

This simple and low-cost proposal uses simple decanting sedimentation for depositing suspended particles in rainwater. In short, water is collected from the roofs, the first waters of the rainy season are discharged directly into the sewage system (washing of the roofs), rainwater is stored, simple decanting occurs (considering the draining of excess rainwater), and water is supplied from rain to non-potable use points. We can define this collect model as the "diverter type" (Figure A2 in Appendix A) as defined by Herrmann and Schmidab [35]. It is important to note that these systems have the advantage of saving potable water from public water supply systems and reducing the impact of rainwater in the public drainage system and the risk of floods. Consequently, rainwater collected for non-potable consumption can be used.

The system proposed for the case of Beira can potentially reduce the consumption of potable water from the supply network by about 40%, or about 183,000 liters per year; in a multifamily building with two families of five persons each, this amounts to approximately 18,830 liters per person, within the parameters defined by Herrmann and Schmida [35], where for one family the average savings in drinking water will be about 30% to 60%.

The city of Beira has experienced constant flooding due to a lack of drainage capacity, despite the importance of freshwater scarcity and environmental management in recent years in the context of rainwater reuse [61]. As a result, flood control has become increasingly important in urban water infrastructure [62,63] for pollution prevention and mitigation, given the high impermeability of soils. Different studies indicate that the implementation of RWH could reduce the volumes and peaks of urban runoff, relieve the pressure of urban drainage systems, and mitigate the environmental impacts of urbanization [43,64], which demonstrates the feasibility of applying this type of system.

Supplementing the water supply with locally collected rainwater is an effective way to improve the efficiency of urban water resource use in this context. This can reduce dependence on conventional water supplies, minimize energy consumption for water transport, minimize downstream contamination, and reduce the amount of effluent discharge and runoff from stormwater systems. Future innovations in water treatment are expected to improve water safety and optimize system configurations to increase energy efficiency and infrastructure resilience. These innovations are necessary to ensure that aging water infrastructure does not pose a threat to public health, and to provide reliable water supplies, reduce water prices, and improve energy efficiency, thereby enhancing economic development and quality of life.

For rainwater harvesting (RWH) to be economically viable, the costs of investment, operation, and maintenance must be balanced with the cost of public water supply. There is a nonlinear relationship between the amount of rainwater available, the amount used for different purposes, and the cost of alternative water sources. On-premises solutions have the advantage of greater flexibility and customization for each user, which can also have indirect benefits. However, there are also negative implications to consider, such as limited availability of rainwater during prolonged periods of drought, inconsistent rainwater quality due to variability in pollution, the potential for mineral-free rainwater to cause nutritional deficiencies, initial investment costs for harvest components, insufficient maintenance, and limited storage space in buildings.

As cities continue to grow, it is essential to acknowledge the various consequences of this expansion, such as increased air pollution, extreme temperatures, heat island effects, floods, and water shortages; incorporating nature-based solutions (NBS) offers an alternative to mitigate these impacts. These solutions perform a range of ecosystem functions that regulate the urban water cycle, reducing the risk of flooding and degradation of aquatic ecosystems [65].

Water retention systems in urban spaces, which can be applied and replicated at different scales and in various urban contexts, climates, and geographic locations, are a particularly viable solution due to their low investment cost. In addition to capturing and draining excess water, these systems regulate air temperature and reduce heat island effects. Implementing greener areas also enhances human well being by creating aesthetically pleasing landscapes and gardens, unlike traditional systems such as street drainage grids. Nature-based solutions, specifically water retention systems, offer a holistic solution that integrates water drainage and purification [66]. According to the Nature-Based Solutions Catalog (NBS) published by the Sendzimir Foundation [66], there are various urban strategies for collecting, storing, and treating water, including retention lakes, bioretention systems, retention ditches, infiltration trenches, bio-retention beds, green roofs, and permeable pavement, among others.

5. Conclusions

The concept of a "Sponge City" refers to the capture and use of rainwater for various purposes within buildings in order to reduce reliance on the public water supply system and promote the efficient use of water resources. This can be achieved through the installation of collection pipes and designs that are properly sized and planned based on the size, location, and rainfall intensity of the building and the purposes for which water is needed.

The adoption of rainwater harvesting (RWH) practices in buildings can provide several benefits, including economic and social advantages for end users through reduced municipal water bills, and environmental benefits through the conservation of water resources. In this study, it is estimated that RWH could reduce 183 thousand liters of water per year in a multifamily building with 10 persons.

In addition to the direct benefits of RWH, there are also indirect benefits that should be considered. For example, the installation of large-scale RWH systems in densely populated areas can help reduce peak flow rates in rainwater drainage systems, reducing the risk of urban flooding. This is particularly important in regions such as Beira, where the high permeability of soils and proximity to sea level make flood prevention a key concern in the context of climate change.

To optimize the benefits of RWH and the adoption of Sponge City practices, further interdisciplinary research is needed. This may include studies on human water consumption patterns, technical and social analyses to improve RWH efficiency, and efforts to engage the community in enhancing rainwater quality and raising awareness about RWH practices. It may also be possible to determine the potability of collected rainwater in Beira through the use of a simple disinfection system, which could further promote the sustainable use of water resources in combination with potable water from the public supply network.

Overall, by capturing and using rainwater for various purposes within buildings, RWH practices can help to reduce reliance on the public water supply system and promote the efficient use of water resources. In addition to providing economic and social benefits for end users and preserving the environment, adopting RWH practices can also have critical indirect benefits, such as reducing the risk of urban flooding and contributing to the resilience of communities in the face of climate change.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su15032276/s1, Table S1 Rainfall data for the City of Beira, Mozambique (1991–2020).

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Appendix A

Figure A1. The block where the building selected as a reference in this study is inserted.

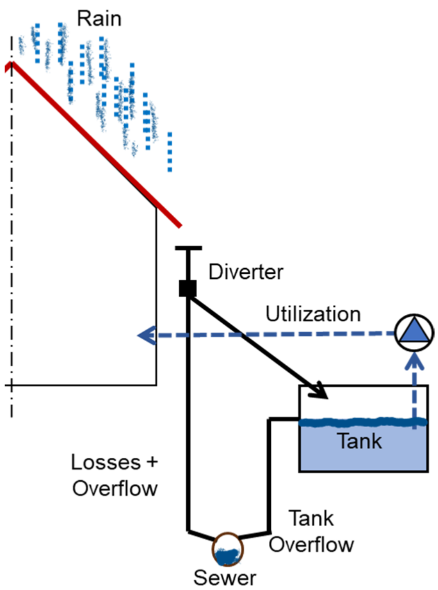

Figure A2. Diverter type rainwater usage system defined by Herrmann and Schmidab (adapted from [35]).

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