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## Article

# Application of the Kilimanjaro Concept in Reversing Seawater Intrusion and Securing Water Supply in Zanzibar, Tanzania

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**Abstract:** There is escalating salinity levels on small islands due to uncontrolled groundwater extraction. Conventionally, this challenge is addressed by adopting optimal groundwater pumping strategies. Currently, on Unguja Island (Zanzibar), urban freshwater is supplied by desalination, which is expensive and energy-intensive. Hence, desalinization cannot be afforded by rural communities. This study demonstrates that the innovative Kilimanjaro Concept (KC), based on rainwater harvesting (RWH) can remediate seawater intrusion in Unguja, while enabling a universal safe drinking water supply. The reasoning is rooted in the water balance of the whole island. It is shown that if rainwater is systematically harvested, quantitatively stored, and partly infiltrated, seawater intrusion will be reversed, and a universal safe drinking water supply will be secured. Water treatment with affordable technologies (e.g., filtration and adsorption) is suggested. The universality of KC and its suitability for small islands is demonstrated. Future research should focus on pilot testing of this concept on Unguja Island and other island nations.

**Keywords:** Kilimanjaro concept; rainwater harvesting; seawater intrusion; sustainable development; zero-valent iron; water quality

## 1. Introduction

There is a growing interest in establishing sustainable water management systems to secure safe drinking water supply, sustainable agriculture, and ecotourism on small islands worldwide [1–8]. In essence, a regional approach considering the whole island as a region should be regarded as a key approach for the implementation of affordable, ecologically sound, and sustainable practices for integrated water management [9–12]. However, assessing the sustainability of water management approaches is a challenging

task since it involves a dynamic and simultaneous balance among cultural, economic, environmental, and social aspects. In most cases, these aspects are interlinked and often perceived as conflicting with each other [2,9,12]. For example, should the focus be water for tourists on an island when water for subsistence farming to secure livelihoods and food security is lacking?

A number of scientific publications, dissertations, and technical documents have emerged to critically evaluate the sustainability of water management on small islands [1–3,5,8,13–17]. However, the application of existing and well-established sustainability assessment largely requires a complex set of tools. This makes data collection, processing, and analysis expensive, time-consuming, and requires external expertise. This situation makes water management on small islands of developing countries a daunting task. Governments in developing countries often rely on foreign expertise and technology transfer [18–21]. For example, three medium-sized German companies have recently formed an alliance to improve safe drinking water provision in Unguja Island, Tanzania [22]. The operation enabled around 2000 residents in the regions of Michamvi and Kijito Upele to have access to “clean and affordable” drinking water [22,23]. The cost of this operation is not discussed herein, but it suffices to state that the system was installed to monitor water quality throughout the entire island. Having been equipped for instrumental water analysis, Unguja can start a new era for routine water quality monitoring [24,25]. It is certain that water desalination is an expensive technology [26–28]. Moreover, meeting the water needs of just 2000 people is insignificant, given a total population of more than 800,000 inhabitants on the island. Therefore, more affordable and applicable systems are still needed on Unguja Island.

Small islands and coastal regions are currently suffering from increased sea level rise and seawater intrusion [29,30]. Related impacts include: (i) limited freshwater availability for domestic, industrial, municipal, and recreational uses, and (ii) shifts in seawater-sensitive habitats. Population growth and increased industrialization are further exacerbating the situation. On certain islands, such as Unguja, the growth of the tourism sector has worsened the problem [2–6]. These related challenges have been investigated from many perspectives using various methodologies [4–6,29,30]. Mixed findings have been reported on some aspects, but there is a consensus that there is a need for more research for the development of sustainable water resources [29–31]. Although rainfall has been acknowledged to be the root water source for Unguja, and its good quality is generally recognized [9,11,29,32,33], RWH as a source of water supply has only received cursory attention. For example, RWH has been considered only as a technology for low-income communities or as a source of non-potable water in urban and peri-urban communities [18,21,23].

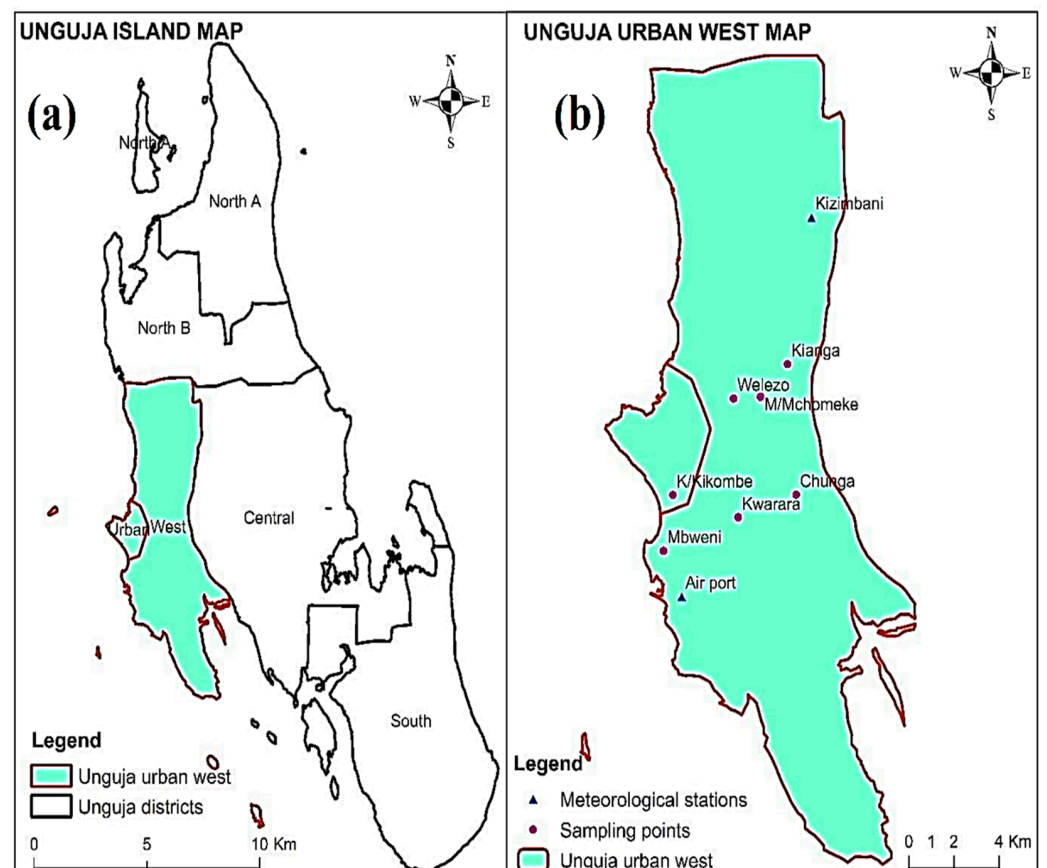
In the year 2018, a novel concept called the Kilimanjaro Concept (KC) for regional integrated water management was introduced based on RWH [10,11,34]. KC is rooted in harvesting, storing, and partly infiltrating rainwater to control runoff and improve groundwater recharge. KC clearly advocates for large-capacity storage and long-distance transportation (if applicable) of harvested (and treated) rainwater [11]. Thus, adopting KC implies that safe drinking water is provided from rainwater, which is relatively less polluted than surface water, and easier to treat using affordable technologies than seawater [11,29,34]. RWH reduces surface runoff, causing soil erosion and flash floods by promoting artificial local infiltration, while groundwater recharge is increased at the same time. In particular, KC can complement or even completely replace water desalination by harvesting and storing enough rainwater or capturing reasonable amounts of water from permanent and seasonal streams [11]. In addition, using water blending, calculated amounts of seawater (or saline cave water) can be mixed with rainwater to have water meeting both potable and irrigation water quality guidelines [11,34]. Blending seawater and rainwater as a supplementary source of drinking water is particularly important during periods when RWH alone cannot meet water demand. Additionally, compared to rainwater, the blended water is enriched in minerals (e.g.,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ).

The present study posits that the KC provides a novel framework for mitigating seawater intrusion and securing water supply for small islands through the integration of RWH systems. The present study aims to: (i) develop a framework for the implementation of KC on Unguja Island, and (ii) propose the most suitable approach to consider new stakeholders (e.g., industries, farmers) and their water demand. To achieve this, the proposed approach aims to consider all stakeholders, including farmers, industrialists, and households, to achieve sustainable water management in isolated islands worldwide. In addition, integrating indigenous knowledge in such an integrated water management will render it efficient and sustainable.

## 2. Materials and Methods

### 2.1. Description of Zanzibar Island

Zanzibar is an archipelago located in the Indian Ocean about 37 km off the east coast of mainland Tanzania [14,35]. Zanzibar belongs to the United Republic of Tanzania. The archipelago of Zanzibar consists of two major islands: Unguja and Pemba, both in a tropical climate [36]. Compared to Pemba, Unguja is the larger island, hence is often referred to as Zanzibar. Thus, in this paper, the term “Zanzibar” is used to mean Unguja Island (Figure 1). Zanzibar is 86 km long and 39 km wide, with an area of 1660 km<sup>2</sup> and a population density of 460 persons km<sup>-2</sup> [4,14]. This study considers Unguja as a model island to demonstrate the applicability of KC for efficient water management.



**Figure 1.** A map of the island of Zanzibar (Unguja) indicating different regions (a) and wards of the Urban West region (b) where the original sampling took place. Used with permission from Ali and Rwiza [31].

According to the 2012 national census, Zanzibar had a population of 896,761, with an annual growth rate of 2.8% [14]. Zanzibar is bestowed with magnificent coastal areas offering diverse opportunities for tourism development [2–6]. Coastal areas of Unguja

have been the cornerstone of tourism-based activities in Zanzibar for some decades [2,3]. This has contributed to an uncontrolled abstraction of groundwater, which has now caused seawater intrusion [4,14].

Zanzibar experiences a predominantly hot, tropical climate with two rainy seasons and an average temperature of 32 °C. The first rainy season occurs between March and May, and the second one occurs from October to December. Zanzibar receives an average annual rainfall of about 1350 mm, which heavily depends on the season and the change of monsoon [1,31,36].

Originally, Zanzibar was covered with dense rainforest, but during the 19<sup>th</sup> century, the island was progressively cleared for plantations and human settlement. Only a small part of the original vegetation is currently protected as part of a nature reserve. In the north of the island, there are large plantations of sugarcane and rice. The unfertile east of the Unguja is covered with dry bushlands [13]. Note that the removal of natural forests due to deforestation promotes the rapid generation of a large volume of runoff [37–39]. In turn, this reduces infiltration and groundwater recharge, and subsequently, baseflow. Therefore, RWH, and subsequent artificial infiltration seeks to reverse these hydrological impacts by increasing infiltration and groundwater recharge, and hence, base flow. This base flow then forms a freshwater lens that floats above the dense seawater. A detailed discussion of how RWH systems affect the surface and groundwater hydrology is presented in earlier reviews [39]. Given that the island is only 86 km long, it is possible to install storage tanks in the east and transport rainwater harvested elsewhere for storage and convey it back for subsequent use. In addition, excess water can be infiltrated on-site to reduce erosion and increase local groundwater recharge.

## 2.2. Water Resources in Zanzibar

Freshwater is always a limited resource on oceanic islands. A study of pockets of land at the coast of Kenya and Tanzania, including the Comoros, pointed out rainfall scarcity as one of the reasons for salinity in groundwater [40]. The low rainfall patterns and decreased rainfall events in these areas were attributed to variability in the Indian and Pacific oceans and to the El Niño-Southern Oscillation [40]. A different study indicated rainfall events in the magnitude of 1500–2000 mm/year on a small island of Mayotte in the Indian Ocean [41]. Compared to Zanzibar, the Comoros, and Mayotte, other African islands, such as Cape Verde, receive far less average annual rainfall in the range of 200 to 600 mm/y [42]. Another study on Hawai'i Island projected an increased groundwater recharge of 48,600 m<sup>3</sup> per hectare over 50 years through conservation of a natural forest to avoid high rates of actual evapotranspiration [43]. Recently, for Samoa Islands (average annual rainfall of 1750–5000 mm/y), it has been projected that 57% of the annual rainfall goes to groundwater recharge, 8% (evaporation), 15% (evapotranspiration), and 20% as surface runoff [44]. However, thanks to the high amount of annual rainfall on Zanzibar Island (1350 mm), there is enough water on the island to enable the successful implementation of KC. There are two types of water resources in Zanzibar: surface and groundwater. This section summarizes the water balance for Zanzibar as reported in 2010 in an earlier work entitled Water Balance Assessment in Unguja, Zanzibar [4].

### 2.2.1. Surface Water

There are few rivers on Zanzibar Island, consisting of coastal and inland rivers. Coastal rivers reach the ocean while inland rivers do not. Coastal rivers are mostly located at the northwest of the island, and these are smaller rivers that do not currently represent significant water resources. Inland rivers are mainly situated in the central part of the island, and these include Pangen, Mwera, and Kinyasini rivers. Inland rivers disappear into the sinkholes occurring in the limestone or karst geological system. Inland rivers certainly contribute to the groundwater recharge through surface water–groundwater interactions.

### 2.2.2. Groundwater

Groundwater is currently considered the primary source of water in Zanzibar. Being an oceanic island, groundwater resources in Zanzibar occur in the form of freshwater lens, which floats above the deeper saline aquifer. It is thus very crucial to maintain the balance of fresh and saline water to prevent seawater intrusion into the inland groundwater system. Zanzibar also has a considerable number of springs. Zanzibar Town had its first supply from two springs: Bububu and Mtoni. Two other important springs are Kiwani Bay in the northwest and Kombeni in the south of the island. A previous study examined the hydrological processes and estimated the groundwater recharge of Zanzibar to be  $564.73 \text{ mm}^3 \text{ y}^{-1}$ , equivalent to 680.4 mm/year while assuming an average runoff coefficient of 50% [4]. This groundwater recharge is about 24% of the total annual rainfall. In this previous study [4], groundwater recharge was estimated using a Soil and Water Assessment Tool (SWAT) model. The model applied ASTER GDEM datasets in which digital elevation, soil maps, land cover map, and weather data were used as inputs. The model was able to predict, with a fairly good fit, surface runoff, evapotranspiration, and groundwater recharge. However, in the model, ET is estimated as a lumped component, rather than partitioning it into evaporation (E) and transpiration (T). Thus, the individual contributions of E and T to the regional water balance remain unknown.

### 2.2.3. Water Balance

For a given system with well-defined spatial and temporal boundaries, the water balance essentially relates the inflow, outflow, and storage of water in a system. The water balance is derived by calculating the input, output, and storage changes of water. The major water input is from precipitation, while the major uncontrolled output is from evapotranspiration, including transpiration through vegetation. In the case of Zanzibar Island, the regional water balance is given as:

$$\text{Input} = \text{Rainwater} = 100\% \quad (1)$$

$$\text{Output} = \text{ET}(40\%) + \text{GWrecharge}(24\%) + \text{Wateruse}(1.3\%) + \text{Runoff}(36\%) \quad (2)$$

where *GW* stands for groundwater and *ET* stands for evapotranspiration.

The absolute value of the total output is 101.3%, which is within the range of acceptable uncertainty. The most important feature of this balance is the high proportion of unproductive water flowing free into the sea as runoff (36%). The model presented by [4] predicted that 44.1% of the rainfall evaporates to the atmosphere as evapotranspiration, while 31.8% is lost as surface runoff and 24% infiltrate and make the total groundwater recharge. Thus, KC seeks to convert the bulk of the runoff into water for drinking purposes and other livelihood activities. The 36% runoff in the case of Zanzibar can be effectively harvested through rainfall harvesting systems [31,35,45], which seeks to convert (at least a fraction of) the surface runoff (>30%) into productive uses.

### 2.3. Current Water Management in Zanzibar

This section is based on the final report of an international collaborative work on the potential of RWH in Zanzibar presented fourteen years ago [18]. According to the same report, the starting point was the fact that Zanzibar's main water source is groundwater. In this case, RWH technologies were to be introduced to improve water availability. The report concluded that the project needed an estimated budget of USD 6,420,000 to start, and about eight years to be implemented. However, previous sections demonstrated that little has been achieved to date besides providing water to a mere 2000 people. Note that this report was prepared as part of the government of Zanzibar's quest for strategies to facilitate an environment conducive to developing an integrated water resource management (IWRM) plan. Groundwater, rainwater, and surface water have been considered, but not in the same perspective like in KC. The most common point between the IWRM and KC is the centrality of RWH and the involvement of all key stakeholders, including farmers, local communities,

government, non-governmental organizations (NGOs), and the private sector. External partners, including donors, are also considered [18].

### 2.3.1. Surface Water, Cave Water, and Groundwater

Zanzibar has both perennial and ephemeral springs and streams. The discharge from perennial streams is reduced drastically during the dry season. During the rainy season, all these rivers rapidly discharge substantial amounts of water into the Indian Ocean. Internal streams discharge into the coral limestone sinkholes. Many caves filled with water are available, of which some have turned saline, particularly in the coastal region [46].

Since 1997, river discharge data have been available for Zanzibar. These data have enabled a purposeful damming of rivers and the diversion of water to cropped land for irrigation. According to [18], the rivers Mwera and Kipange had enough water to irrigate 585 ha of crops during most of the dry and rainy seasons. In the context of KC, the volume of water which can be stored for non-agricultural uses should be considered as well.

Springs of excellent drinking quality are available in Zanzibar. For example, the main source of domestic water supply to Zanzibar Stone Town is a spring that was developed and protected in 1923 [18]. Groundwater abstraction is widespread in Zanzibar, to the extent that almost every household would want to own a well. Abstraction methods commonly used include boreholes and open shallow wells (15–20 m). Since the 2000s, the government has been overwhelmed with its role of monitoring both the quantity and quality of groundwater. Artificial groundwater recharge is not really practiced.

### 2.3.2. Rainwater Harvesting in Zanzibar

Data presented in [18] revealed that, on a regional scale, Zanzibar receives a colossal volume of rainwater amounting to 2.4 km<sup>3</sup> per year. The island currently utilizes only 1.3% of the total rainwater for domestic water supply and irrigation, while 24%, equivalent to 0.576 km<sup>3</sup> per year, runs off to the Indian Ocean. Groundwater recharge and total evapotranspiration account for 24% and 40%, respectively. Researchers [18] used GIS mapping based on five-year satellite data and annual average rainfall recorded between 1950 and 1993 at 14 weather stations to estimate the amount of rainfall received on the island of Zanzibar. Historical and near real-time hydrological data derived from remote sensing and GIS data were used in estimating rainwater partitioning. This water balance relates closely to the one presented in Section 2 above and corresponds to what was reported previously in the literature [4]. Noticeably, there is evidence of increased runoff over a 3-year period attributed to land-use changes, including urban development. The increased urban development and the corresponding increase in impervious surfaces hinder rainfall infiltration while promoting runoff may account for this trend in runoff data. According to the report, agricultural production is almost exclusively rainfed, but appropriate rainwater harvesting and storage techniques for reducing runoff and erosion are currently lacking.

There are many technological options of RWH currently applied in Zanzibar. Some of them have been known to the local population for many centuries [33]. Systems based on indigenous knowledge offer sustainable solutions but were often misconstrued as primitive during the colonial period, and with modernization, these systems are gradually being lost. Short- and long-term storage systems are used for crop production, domestic activities, and livestock production. Available RWH systems are subdivided into in-situ and ex-situ runoff water harvesting techniques [18].

### 2.3.3. In-Situ RWH Systems

In-situ techniques are knowledge-based and do not require capital investment (no money expense). In-situ techniques need local manpower and technical know-how for their implementation and maintenance. In-situ RWH Systems use a large array of technologies to produce “green water” (stored in soil) for agroforestry, crop, and pasture production, and upgrading of rain-fed farming systems. Common technologies include ditches, drainage

level, bunds, pits, terraces, tillage, and trenches, which are often combined with improved agronomic practices, such as soil fertility management [18].

#### 2.3.4. Ex-Situ Runoff Catchment Systems

Ex-situ runoff harvesting systems require the construction of conveyance and storage structures, such as check dams, tanks, ditches, and terraces. In-situ RWH techniques are directly used for agriculture, while ex-situ runoff techniques are flexible, hence can be used for several purposes, even at very distant locations [11]. Large-scale roof catchment water harvesting systems require the construction of either above or below ground storage tanks and belong to the ex-situ runoff harvesting systems. Ex-situ systems conventionally store water in storage structures, such as ferro-cement tanks, masonry tanks, recharge wells, spherical tanks, and underground tanks. In this case, the harvested water is termed “blue water” and is mostly used as drinking water or domestic water, and for livestock production. It is obvious that upon appropriate treatment, blue water can be turned into “green water”. Moreover, a dual design can be adopted such that only a fraction of blue water to be used for potable purposes is treated to attain acceptable water quality standards. Conventional groundwater recharge systems also require the construction of storage and recharge structures, such as a network of boreholes, infiltration pits, dams, ponds, and wells, which will facilitate recharge of aquifers.

KC is about making both blue water and green water the first option for integrated water resources management. Accordingly, all available technologies for RWH, including check dams, infiltration ditches, irrigation canals, lined and unlined ponds, sand and subsurface dams, underground tanks, and weirs, shall be used to harvest as much rainwater as possible. Harvested rainwater shall then be rationally used to cover all needs.

Beyond domestic water supply, the KC can be extended to the provision of water to support activities to enhance livelihoods and food security [11,34]. To achieve this, KC will harness existing knowledge on RWH techniques in agriculture. These techniques include both in- and ex-situ RWH systems with storage. In-situ and ex-situ water harvesting systems have been the focus of several studies in Tanzania and elsewhere [45,47,48].

### 3. A Framework for Implementing the Kilimanjaro Concept in Zanzibar

#### 3.1. Analysis of Rainwater Water Supply-Demand Relationships

In the current work, a theoretical approach has been applied to analyze the relationship between the extent of runoff harvesting and meeting water needs on Zanzibar Island. Much of the impetus for this work originates from two recent works: (i) Ali and Rwiza (2020), wherein the state-of-the-art knowledge on water supply in Zanzibar is discussed [31], and (ii) Qi et al. (2019), wherein the universality of KC is presented [11]. Moreover, the need for RWH for socio-economic activities is emphasized in the current water policy for Zanzibar [49]. Statistics indicate a high potential for rooftop runoff harvesting in the country, with roofs with metal sheets considered as by far the most common roof types in both rural and urban areas (i.e., 74.8 and 93.5%, respectively) [45,50]. Henceforth, the RWH potential for Zanzibar was analyzed using a simple daily water balance model with overall cumulative water storage (Equation (3)). The analysis incorporated the performance parameters for the dry season, including the number of days without water (NWD) (Equation (4)), and rainwater usage ratio (RUR) (Equation (5)). This analytical approach has been used in several earlier studies on RWH systems [11,34,51–54]. In addition, the reliability of the harvestable rainwater system was determined (Equation (6)), which indicates the percentage of time when the demand is fully met.

$$V_t = V_{t-1} + Q_t - Y_t - O_t \quad (3)$$

$$\text{NWD} = \frac{T - \sum_{t=1}^T \text{WD}}{T} \times 100 \quad (4)$$

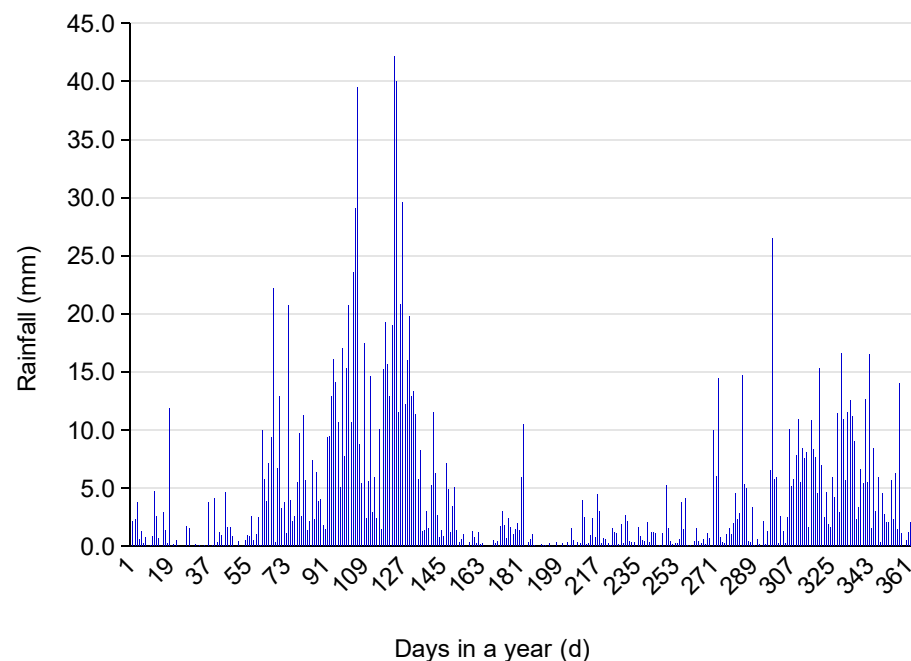


$$RUR = \frac{\sum_{t=1}^T Y_t}{\sum_{t=1}^T Q_t} \times 100 \quad (5)$$

$$\text{Reliability} = \frac{\text{Days fully served in a year}}{\text{Total days in a year}} \times 100 = \frac{\sum_{t=1}^T \text{WD}_t}{T} \times 100 \quad (6)$$

where,  $Q_t$  is the rainwater harvested on the  $t_{th}$  day;  $V_{t-1}$  is the volume of rainwater stored in the tank at the beginning of the  $t_{th}$  day;  $Y_t$  is the rainwater available for consumption or use during the  $t_{th}$  day; WD is the day on which the demand is fully met;  $T$  is the total number of days in the year or years considered;  $V_t$  is the cumulative volume of water stored in the rainwater tank after the end of the  $t_{th}$  day, and  $O_t$  is the overflow volume on the  $t_{th}$  day. All volumes are expressed in liters.

In the current study, all 365 days of the year were considered, and a runoff coefficient of 80% for the metal roofs and daily rainfall data were used in the analysis (Figure 2). Fixed demand conditions were considered, keeping in mind the fact that the minimal recommended daily water consumption per person is 20 liters [19] and that the average household size is 5.6 members. Two case studies were considered for illustration purposes: (1) individual households and (2) a hotel business as a representative enterprise in the tourism industry.



**Figure 2.** Average daily rainfall data for Zanzibar for the period 2011–2018 (Source: Tanzania Meteorological Agency, Zanzibar office).

### 3.1.1. Individual Households

For the individual household case study, various demand sizes were investigated between 120 to 840 L per day (Figure 3), and the household size approximated to 6 people. Roof catchment sizes were maintained at 100 m<sup>2</sup> for lower demand (Figure 4) in the range of 120 to 420 L per day, while a value of 200 m<sup>2</sup> was used for demand above 420 L per day. For the hotel industry, these were treated as medium-intensive industries for which the policy [55] estimated a daily demand of 20 m<sup>3</sup> per hectare, and this value was adopted in this study. The corresponding catchment size was varied between 2000 and 16,000 m<sup>2</sup> (Figure 5). In all cases, a storage size was estimated, corresponding to optimal reliability. A target reliability of at least 70% was used as recommended by Ndomba and Wambura [47]. Note that the water captured by springs and streams is not considered in this model, while artificial infiltration can be regarded as part of the runoff harvested.

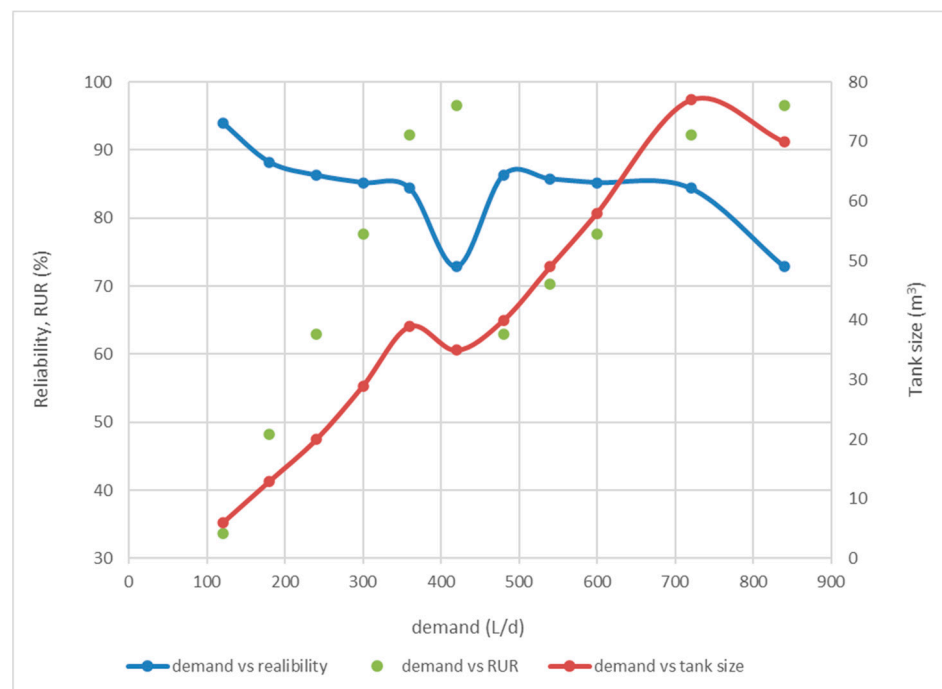


Figure 3. Effects of individual demand variations on harvested rainwater storage and reliability.

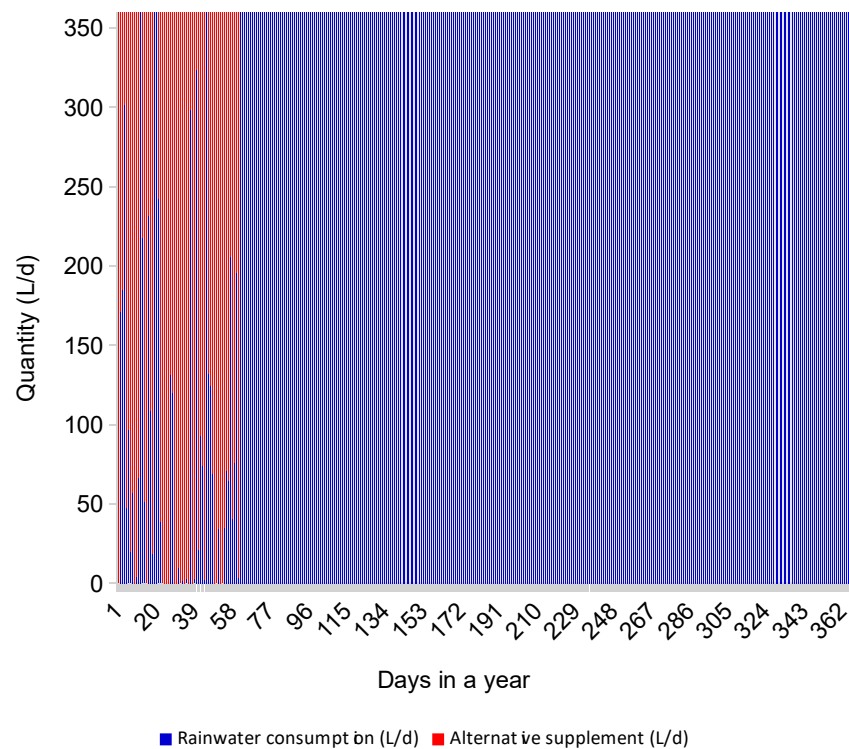
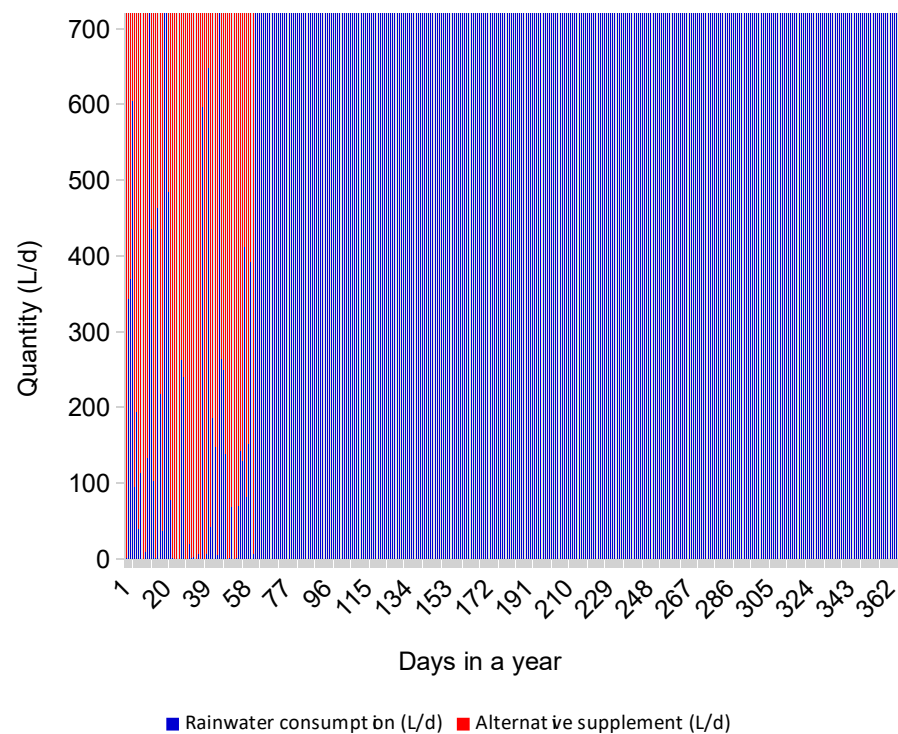


Figure 4. Daily requirements supplied through RWH (blue bars) and the corresponding required supplementary supply (red bars) to meet a demand of  $360 \text{ L d}^{-1}$  for a given family for a catchment area of  $100 \text{ m}^2$ . Note that for any given day, the demand that is not met through RWH, is met through supplementary sources to meet the total demand (i.e.,  $360 \text{ L d}^{-1}$ ).

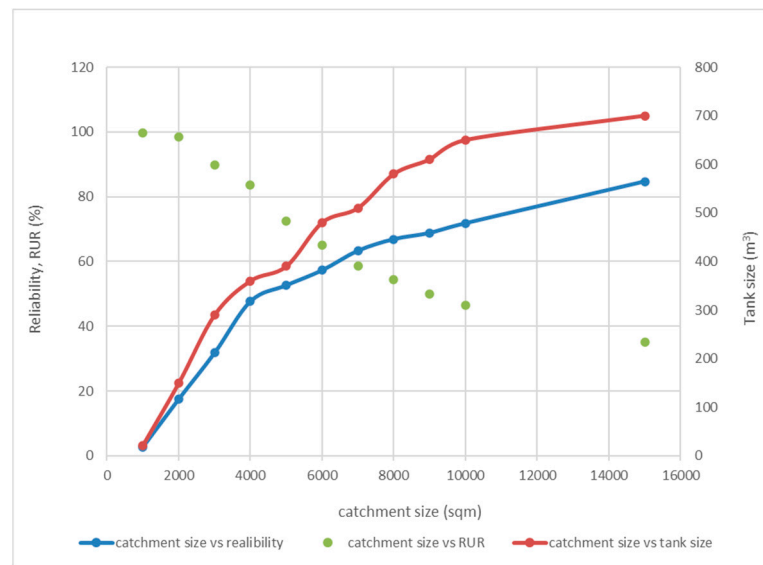


**Figure 5.** Daily requirements supplied through RWH (blue bars) and the corresponding required supplementary supply (red bars) to meet a demand of  $720 \text{ L d}^{-1}$  for a given family for a catchment area of  $200 \text{ m}^2$ . Note that for any given day, the demand that is not met through RWH, is met through supplementary sources to meet the total demand (i.e.,  $720 \text{ L d}^{-1}$ ).

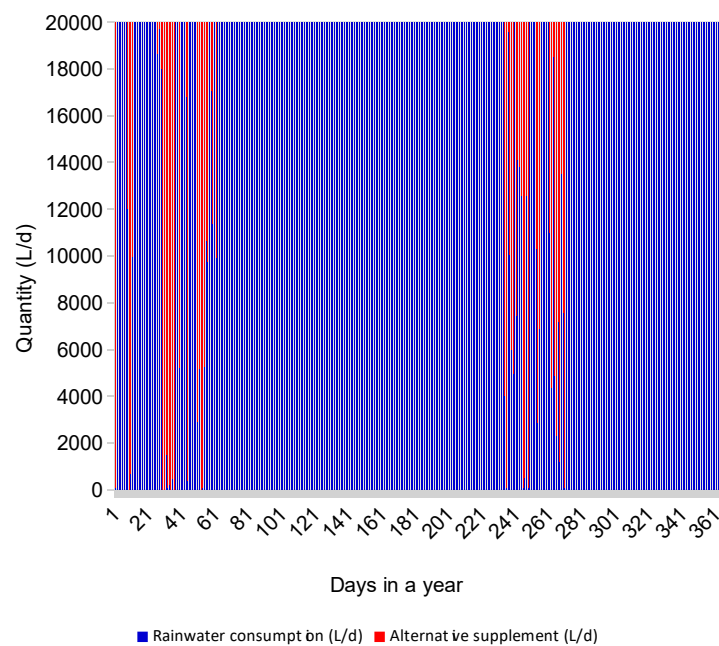
From the analysis, the focus was on maintaining a reasonable RUR and high reliability. For the individual household case study, an optimal storage ( $\text{m}^3$ ) of 39 and 77 is recommended for catchment sizes ( $\text{m}^2$ ) of 100 and 200, respectively (Figure 3). Using storages of  $39 \text{ m}^3$  and  $77 \text{ m}^3$ , Figures 4 and 5 show that 87.4% of the household demand will be met through RWH, and a corresponding RUR of 92.2% and 308 days of full demand supply will be achieved. Hence, alternative complementary water sources (e.g., groundwater, springs) will need to meet the remaining demand of only 12.6%. The complementary sources can be easily covered by capturing water from springs and streams. In the absence of such alternatives, seawater can be blended with harvested rainwater to meet drinking water quality standards.

### 3.1.2. Hotel Industry

For the hotel industry case study, a reliability of above 70% was achieved at a catchment of at least  $10,000 \text{ m}^2$ . A RUR of 46.5% was achievable at a catchment of  $10,000 \text{ m}^2$ , while with an increased catchment to  $15,000 \text{ m}^2$ , RUR was lowered to 35%. This implies that there is more loss as overflow when the total inflow volume exceeds the storage capacity at higher catchment area than lower ones under similar conditions of demand and rainfall data. For a higher reliability of 84.7%, an optimal storage of  $700 \text{ m}^3$  is recommended at a catchment size of  $15,000 \text{ m}^2$  (Figure 6). With that storage of  $700 \text{ m}^3$ , it is shown that 89.8% of the hotel demand will be met through RWH (Figure 7). Hence, alternative complementary water sources will need to meet the remaining demand of only 10.2% to ensure a full demand supply in 56 days, which is not fully met by locally harvested rainwater.



**Figure 6.** Effects of catchment area variations on harvested rainwater storage and reliability in hotel industry.



**Figure 7.** Daily requirements supplied through RWH (blue bars) and the corresponding required supplementary supply (red bars) to meet a demand of 20,000 L d<sup>-1</sup> for a given hotel industry for a catchment area of 15,000 m<sup>2</sup>. Note that for any given day, the demand that is not met through RWH, is met through supplementary sources to meet the total demand (i.e., 20,000 L d<sup>-1</sup>).

### 3.2. Meeting Water Demands under KC

Overall, the analysis displayed a good potential for KC to be adopted in Zanzibar to meet household as well as hotel industry water requirements. A dual supply approach is required for full demand supply, where local RWH meets the bulk of the water supply, while other sources meet the remaining demand. In this regard, complementary sources include groundwater, springs, and blending of seawater and rainwater, but these are necessary only when the demand exceeds the total amount of rainwater (local and foreign). As highlighted earlier, besides water supply, KC concept also improves the quality of groundwater through controlled local infiltration and artificial recharge of harvested rainwater.

It is obvious that rainfall varies daily (Figure 2), while consumers' daily demands are supposedly fixed. As a result, daily harvestable rainwater fluctuations are inevitable, as displayed in Figures 5 and 7, which impact the water available to meet the daily demand. As displayed in Figures 5 and 7, with respect to the storage facility for such days, the harvestable amount was insufficient. Thus, RWH must be extended and/or water supply from alternative sources, such as springs and streams, should complement rainwater so that consumption remains limited to the demand size. In addition to RWH, Zanzibar should consider pumping water from permanent streams [11], and such a decision should be based on the yield of the source, the demand to be served, and ecosystem maintenance. For areas with limited alternative water sources, [46,48] introduced RWH operational strategies under which the impact of varying daily consumption for prolonging the stored harvestable amounts to last longer periods was demonstrated. The authors also introduced a water level monitoring system so that users know when to adjust their consumption from the storage system to avoid exhausting the water. However, this may not be necessary for Zanzibar, considering the abundance of water resources.

Alternatively, for Zanzibar, a dual water supply system integrating KC and other water sources may work better [49]. Figures 5 and 7 show that under given conditions, there were some days when the daily demand will be fully, partially, or not met at all. For proactiveness, water levels may be monitored with gauges on the storage system, guiding all users upfront to know when to seek or refill the storage system with an alternative supply. In the case of filling the same storage with water from different sources, the quality has to be monitored so that water from one source does not contaminate the other sources. For example, groundwater resources are prone to geogenic contamination, with salinity and fluoride contamination being the common ones [10,11]. The analysis of raw and treated rainwater to assess whether it conforms to drinking water guidelines is critical in safeguarding human health. At least once after a rainy season, rainwater quality should be checked through laboratory analysis [24,25]. Therefore, the analytical laboratories currently available on the island are critical for the implementation of KC.

### 3.3. Overcoming Seawater Intrusion via KC: The Processes and Preconditions

KC entails harvesting as much runoff and rainwater from various catchments, including roofs, impervious natural surfaces, such as rocks, mountains, and ground surfaces. Subsequently, depending on the physicochemical and microbiological quality of the harvested water [34], several scenarios exist for using the harvested rainwater. In cases where the water is confirmed to meet drinking water guidelines, the rainwater can be used for household drinking water supply without treatment. Note that the proposed RWH system comprises pre-treatment systems, such as a first flush tank and coarse filter. Still, if the water quality violates drinking water guidelines, appropriate low-cost water treatments, including the use of iron-based filters, can be used for water treatment before supplying drinking water to communities. In this regard, RWH systems are used to either substitute or complement drinking water supplies based on groundwater abstraction. In turn, this will reduce excessive groundwater abstraction and the associated drop in groundwater levels.

In some cases, rainwater and runoff from certain land uses, such as crop fields and grazing areas, may have high loads of sediments and other contaminants. Due to excessive contamination, such water may not be ideal for direct use as drinking water with or without low-cost water treatment. One option to overcome this is to first inject runoff or rainwater into the groundwater system through well-planned and designed local infiltration points. As the water infiltrates, significant removal of contaminants occurs via natural soil filtration and adsorption to the soil and aquifer matrix. The mechanisms responsible for the removal of contaminants are similar to those reported in soil aquifer treatment systems [56,57], which have been widely used for the treatment of runoff and wastewaters for irrigation. The injection of runoff into the groundwater system constitutes artificial groundwater recharge. Such well-fields should preferably be located in zones with geologi-

cal materials with relatively high hydraulic conductivity to enable fast recharge and prevent well-clogging. This artificial groundwater recharge via runoff injection will complement natural groundwater recharge processes occurring during and after rainfall events. The increased groundwater recharge will result in a corresponding rise in groundwater levels and total hydraulic heads. Given that freshwater, including rainwater and runoff, have a lower density than saline/seawater, it is envisaged that the artificial recharge process will culminate into the formation of a freshwater lens above the seawater layer. Thus, scope exists that, as groundwater levels rise due to artificial recharge, any subsequent abstraction for drinking water purposes could be limited to the freshwater lens.

The increase in the total hydraulic heads in the groundwater system on the island, relative to the surrounding systems, will, in turn, reduce seawater intrusion into groundwater systems. Moreover, the increase in total hydraulic heads may even reverse the groundwater flow directions. Specifically, according to Darcy's principle, the high total groundwater heads on Zanzibar Island will imply that groundwater may even end up flowing from the island into the seawater system. This will be contrary to the current system, where seawater flows into groundwater systems driven by a drop in groundwater levels and total groundwater heads on the island caused by excessive groundwater abstractions.

Taken together, the application and adoption of KC have three practical implications: (i) a significant reduction in groundwater abstraction due to a shift from groundwater to RWH systems, (ii) a rise in groundwater levels and total heads on the Zanzibar Island relative to the surrounding area due to increased artificial recharge of groundwater systems via runoff injection, and (iii) reduced or even reversal of groundwater flow directions in the long-term. Furthermore, reducing seawater intrusion and providing clean drinking water, the KC concept also has other associated benefits which have been discussed in earlier papers [10,11,34]. Key among them is the potential to couple rainwater systems for drinking water supply and prevention of seawater intrusion on livelihoods and food security by using excessive harvested rainwater for food production, including crops, livestock, and aquaculture.

However, a number of preconditions exist for the successful implementation of KC to address seawater intrusion and associated challenges. These preconditions include:

- (1) Detailed analysis and understanding of the potential for RWH in terms of (i) catchment area and types, (ii) harvestable rainwater and its seasonal and annual variability, and (iii) the physicochemical and microbiological quality of rainwater/runoff;
- (2) Detailed design, costing, and pilot testing of KC, including evaluation of various scenarios as part of the pre-feasibility and feasibility phase;
- (3) Large-scale application and adoption of KC on the island to ensure that the rise in groundwater levels occurs at a scale large enough to achieve the perceived benefits on the whole island;
- (4) A supportive regulatory policy and institutional framework that promotes KC. This may include raising public awareness and the use of legal, economic, and financial instruments, such as incentives/disincentives, to promote RWH systems.
- (5) A need to draw lessons from other similar islands elsewhere (e.g., [15]), to identify relevant concepts that can complement KC. Such lessons may include: (i) the determination of optimal groundwater abstraction to prevent seawater intrusion, and (ii) the use of GIS spatial tools for identifying the optimal location of runoff infiltration points and RWH systems.

### 3.4. Appropriate Low-Cost Water Treatment: $Fe^0$ Filters for Zanzibar

The technology of producing safe drinking water using metallic iron is presented here as one appropriate option for Zanzibar. Its suitability for decentralized communities is historically documented [58–60].  $Fe^0$  filters have secured the safe drinking water provision of the city of Antwerp (Belgium) between 1883 and 1885 [58,60]. Similarly, coupled with other affordable materials,  $Fe^0$ -based systems were proven very efficient to treat water contaminated by radionuclides [59]. More recently, Indian researchers presented a very

robust Fe<sup>0</sup>-based technology for arsenic-free waters [61]. The systems by Naseri et al. [57] are scalable and applicable to communities of various sizes. The Nelson Mandela African Institution for Science and Technology (NM-AIST) in Arusha (Tanzania) has been working on the implementation of Fe<sup>0</sup>-based water treatment technologies since 2015 [24,62–64]. Current works are done in the context of making Fe<sup>0</sup> a key technology in achieving safe drinking water for all [65–68].

Using Fe<sup>0</sup> for water treatment is rooted in the evidence that aqueous iron corrosion produces solid iron corrosion products (iron hydroxides and oxides), which are excellent contaminant scavengers [67,69,70]. Globally, there is more than 170 technological expertise on the topic [71–73], and Tanzania, through the NM-AIST, is already leading in contemporary water research [24,34,60,63,64,70]. This makes the implementation of KC in Zanzibar a truly self-reliant issue for the United Republic of Tanzania. The particular suitability of Fe<sup>0</sup> filters for the treatment of rainwater arises from the evidence that rainwater is mostly contaminated by pathogens and traces of toxic metals (from roof materials) and organic matter (from birds) [11]. In this regard, KC is unique in that it provides a total solution by providing water through RWH, while guaranteeing its quality for various uses through the use of low-cost Fe<sup>0</sup> filters.

### 3.5. *The Economics of KC in Zanzibar*

This section does not provide any cost estimation for the implementation of KC in Zanzibar but just outlines some economic aspects. First, the technology is developed in Tanzania, and the experts are present in Arusha, Dar es Salaam, and Zanzibar. This means that, for consultations, there will be no need to pay flight tickets for foreign experts (whose expertise is more expensive as a rule). Second, the materials needed for the construction of RWH facilities and supply networks are readily available in the local market and do not need any extra effort to purchase. As well, RWH technology promotion in the past has included initiatives, such as the demonstration of system construction and training of local artisans [47]. This makes the implementation even at the individual level feasible and affordable. Cheaper options for storage tanks were investigated, including the use of low-cost materials, such as ferro-cement [4,52]. Third, local civil engineers will have the opportunity to demonstrate their design capacity and ingenuity. Fourth, there are opportunities for local employment creation for several groups of professionals, including those mining sand for water filters and those producing and conditioning low-cost filter materials, such as biochars or metallic iron, for water treatment. Fifth, ecotourism can be boosted on exceedingly small islands, such as Misali, and expanded into Zanzibar and Pemba. Sixth, KC encourages sustainable resource use and offers farmers an alternative income source through the expansion of irrigation. Seventh, Zanzibar and mainland Tanzania will have technical expertise to export to other similar islands by designing, constructing, and running regional RWH systems for water management. Above all, after more than seven decades of international efforts, Zanzibar will achieve integrated water management with domestic expertise. Therefore, KC provides a tool for easily achieving Goal 6 of the UN SDGs: “Ensure the availability and sustainable management of water and sanitation for all”. In addition, Goal 14 (“Conserve and sustainably use the oceans, seas, and marine resources for sustainable development”) is also largely addressed. It is envisaged that the proposed KC will provide relatively cheaper water than the current desalination plants, which are known to be overly expensive and costly to operate [26–28]. However, a detailed comparative economic and financial analysis of KC relative to other technologies, including desalination, will be needed as part of the feasibility study.

### 3.6. *KC as a Helping Hand for Self-Reliance*

KC is a call for Tanzanians and even other Africans to rediscover and reclaim their role in promoting self-reliance in water supply. Researchers [46] have sketched the historical role of rural Tanzanians in their own water supply as follows:

- (1) Pre-colonial period (before 1884): Water was sought from natural surface water sources (e.g., rainwater, streams, and wells). Additionally, men provided labor for the construction of water wells under the supervision of traditional rulers (e.g., chiefs).
- (2) Colonial period (1884–1960): African rulers were dethroned and could no longer conceive and implement public water management infrastructures. Water was sought from existing natural surface water sources and still functioning wells.
- (3) 1961–1991: Rural populations contributed to free labor during the construction of water projects and were then passive beneficiaries, getting water free from public standpipes.
- (4) 1991–2000: Cost-sharing was introduced; the population had to pay fees for the same water.
- (5) 2001 to date: Rural population contributes part of the cost for new water projects (free labor or cash). The full responsibility for the planning, construction, operation and management of water projects is transferred to the rural population. Water supply is ideally community-owned, and fees are paid by villagers.

The most recent Water Supply and Sanitation Act [21,74] has accounted for rural water supply schemes' operational challenges by introducing community-based water supply organizations to replace community-owned water supply organizations. This is in tune with the goal of KC, which promotes reliance on locally available skills and expertise (engineers and technicians included) in operating and maintaining water schemes. The urban population is not addressed as urban water supply can be regarded as modern. It is just noted that the corresponding supply systems (especially large-scale projects) are not conceived and built by Tanzanian engineers, although they have been mostly trained abroad. However, recent initiatives exist to boost the capacity of locally owned companies, with conditions directing foreign companies to enter into joint ventures with local companies as among the main qualifying criteria in tendering. Researchers advocate for complete self-reliance in water supply even where "modern" technologies are to be used [75]. It makes more sense to employ skilled personnel who will train their Tanzanian colleagues than to continue considering that the local academic system is inferior to any other. Science, including applied science or technology, is universal, and Tanzania is not an exception. It is time to start trying and become experts in one or two decades.

A careful look at this historical sketch shows that with the occupation by the Germans (in 1884), African engineers abandoned their art to become workers in colonial "developmental projects" [75,76]. During this German rule and the time under British rule, the colonial administration designed some water supply systems, but not primarily for Tanzanians. The situation was similar to the one described in India by [77]. This is the origin of the African tragedy, not only in water supply. In essence, from 1884 to 2000 (some 116 years), Africans ceased to be designers of their own water supply systems and even other technologies. They were and are still mostly, and at best, associated with the maintenance of installed systems, which come to Africa as part of "Technology transfer" [75]. That is the main reason why all efforts since the 1960s have literally failed. In Tanzania, in particular, even the United Nations Millennium Development Goals (MDGs) were not met [46]. There is no realistic chance that the United Nations Sustainable Development Goals of achieving universal safe drinking water supply by 2030 will be achieved unless something special happens now. KC is regarded as one of these special helping hands for Zanzibar. It is capable of counteracting the coverage limitations of centralized drinking water systems and realizing the possibilities of resuscitating traditional RWHs as part of the solution mix for addressing water-related challenges in not only Zanzibar but also in other developing countries.

The following features qualify KC for water supply in the context of Zanzibar [62]:

- (1) The piping and storage network can be designed and constructed by Tanzanian engineers. In other words, no foreign funds and experts are required. Water desalination is not needed at all. In some cases, seawater can be blended with rainwater to meet



- drinking and/or irrigation water standards to lower the size of the engineered storage capacity, and
- (2) After installation, the system is really low-cost as water is transported by gravity and treated by low-cost technologies [68,78–81]. It is important to insist that water harvesting can be designed on a village-by-village basis. In this case, the municipality coordinates the collection and transport of excess water to larger communities. During periods with low rainfall, water from permanent streams can be captured and used to refill some storage stations;
  - (3) The whole system, including water treatment, is based on local resources and skills. This means that, in one or two decades, this water management could be regarded as a “modern” indigenous knowledge of Unguja. The population of Unguja would have to relearn self-reliance on water supply, including adaptation to external changes;
  - (4) Safe drinking water is accessible to all communities on the island, including women’s groups and village elders.

#### 4. Concluding Remarks

The generic ideas of KC are adapted to the particularities of a site for the first time: Zanzibar Island. Here, water management encompasses groundwater recharge, thus stopping and reversing seawater intrusion. A more detailed, tailored, purposeful survey and design is needed for the successful implementation of KC in Zanzibar. These efforts include the selection of the most affordable, efficient, and sustainable technological options for water capture, storage, transportation, and treatment. The most innovative aspect of KC is that groundwater recharge is part of the concept, and this is achieved by the simplest means (local infiltration). There is thus no extra effort required to develop awareness for the concept of recharging groundwater. The first strength of KC is that it introduces a clear and coordinated approach to harvesting and managing rainwater on a community-by-community basis. The other strength is that no foreign experts are needed, and the system is designed to be sustainable on a self-reliant basis.

KC for integrated water resources management is demonstrated to be an important tool for water supply in Zanzibar. Upon successful application to this island, its application can be first extended to Pemba, the second major island of Zanzibar. Other small islands could follow; in particular, Misali Island can be rehabilitated. Misali covers an area of only one (1) km<sup>2</sup> and is located 10 km off the coast of Pemba, in the channel between Zanzibar and mainland Tanzania [14]. The island is uninhabited because of a lack of freshwater. It has historically served as an important spiritual site for both African and Islamic beliefs. Pre-Islamic beliefs maintain that the island’s coral caves are inhabited by spirits who will ensure good health and wealth. KC offers a simple tool to make Misali more attractive also for touristic activities. Fresh water can be brought by bottling permanent streams from Pemba (or Zanzibar) or harvesting rainwater in Misali. For the implementation of KC, site-specific research is needed to develop a methodology for the design of storage and transportation networks for the understanding of geotechnical aspects before the construction. Pilot-scale installations are needed just to optimize the practicality of the water treatment technologies being considered (Fe<sup>0</sup>-based filters). It is envisaged that once KC is implemented and is fully operational, the desalinization plant will eventually be decommissioned due to its high operational costs.

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## References

1. Ali, M.H.; Sulaiman, M.S. The Causes and Consequences of the Informal Settlements in Zanzibar. In Proceedings of the XXIII Congress of the International Federation of Surveyors, Munich, Germany, 8–13 October 2006. Available online: [https://www.fig.net/resources/proceedings/fig\\_proceedings/fig2006/papers/ts35/ts35\\_01\\_ali\\_sulaiman\\_0320.pdf](https://www.fig.net/resources/proceedings/fig_proceedings/fig2006/papers/ts35/ts35_01_ali_sulaiman_0320.pdf) (accessed on 7 December 2020).
2. Gössling, S. The consequences of tourism for sustainable water use on a tropical island: Zanzibar, Tanzania. *J. Environ. Manag.* **2001**, *61*, 179–191. [[CrossRef](#)]
3. Gössling, S. Causes and consequences of groundwater use: Zanzibar, Tanzania. *Int. J. Water* **2002**, *2*, 49. [[CrossRef](#)]
4. Haji, H.S. *Water Balance Assessment in Unguja Island*; University of Twente Faculty of Geo-Information and Earth Observation (ITC): Zanzibar, Tanzania, 2010.
5. Mtoni, Y.E. Saltwater Intrusion in the Coastal Strip of Dar es Salaam Quaternary Aquifer. Ph.D. Thesis, Ghent University, Ghent, Belgium, 2013.
6. Hansson, E. Groundwater on Zanzibar—Use and Pollutants. Master’s Thesis, University of Gothenburg, Gothenburg, Sweden, 2010.
7. Alberti, L.; La Licata, I.; Cantone, M. Saltwater Intrusion and Freshwater Storage in Sand Sediments along the Coastline: Hydrogeological Investigations and Groundwater Modeling of Nauru Island. *Water* **2017**, *9*, 788. [[CrossRef](#)]
8. Schwebel, M.B. Measuring climate change adaptation in Pacific small island states: Nissology and success. *J. Water Clim. Chang.* **2018**, *9*, 112–123. [[CrossRef](#)]
9. Meter, K.J.V.; Basu, N.B.; Tate, E.; Wyckoff, J. Monsoon harvests: The living legacies of rainwater harvesting systems in South India. *Environ. Sci. Technol.* **2014**, *48*, 4217–4225. [[CrossRef](#)]
10. Marwa, J.; Lufingo, M.; Noubactep, C.; Machunda, R. Defeating Fluorosis in the East African Rift Valley: Transforming the Kilimanjaro into a Rainwater Harvesting Park. *Sustainability* **2018**, *10*, 4194. [[CrossRef](#)]
11. Qi, Q.; Marwa, J.; Mwamila, T.B.; Gwenzi, W.; Noubactep, C. Making Rainwater Harvesting a Key Solution for Water Management: The Universality of the Kilimanjaro Concept. *Sustainability* **2019**, *11*, 5606. [[CrossRef](#)]
12. Bartzas, G.; Komnitsas, K. An integrated multi-criteria analysis for assessing sustainability of agricultural production at regional level. *Inf. Process. Agric.* **2020**, *7*, 223–232. [[CrossRef](#)]
13. Törhönen, M.-P. Land Tenure Confused: Past, Present and Future of Land Management in Zanzibar. Ph.D. Thesis, Teknillinen korkeakoulu, Espoo, Finland, 1998.
14. Mato, R. Groundwater quality degradation due to salt water intrusion in Zanzibar Municipality. *Afr. J. Environ. Sci. Technol.* **2015**, *9*, 734–740. [[CrossRef](#)]
15. Lal, A.; Datta, B. Application of Monitoring Network Design and Feedback Information for Adaptive Management of Coastal Groundwater Resources. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4365. [[CrossRef](#)]
16. Lal, A.; Datta, B. Optimal Groundwater-Use Strategy for Saltwater Intrusion Management in a Pacific Island Country. *J. Water Resour. Plan. Manag.* **2019**, *145*, 04019032. [[CrossRef](#)]
17. Mussa, K.R.; Mjemah, I.C.; Walraevens, K. Quantification of Groundwater Exploitation and Assessment of Water Quality Risk Perception in the Dar Es Salaam Quaternary Aquifer, Tanzania. *Water* **2019**, *11*, 2552. [[CrossRef](#)]
18. The Government of Zanzibar. *An Assessment of Rainwater Harvesting Potential in Zanzibar*; The Millennium Development Goals Center; United Nations Development Programme (UNDP); Tanzania World Agroforestry Center: Nairobi, Kenya, 2007.
19. MOFA (Japan). Country Assistance Evaluation of the United Republic of Tanzania. In *Third Party Evaluation Report*; KPMG AZSA LLC: Dar Es Salaam, Tanzania, 2016.
20. JICA. *Preparatory Survey on Zanzibar Urban Water Distribution Facilities Improvement Project in The United Republic of Tanzania*; United Republic of Tanzania; Ministry Lands, Water, Energy and Environment (MLWEE); Zanzibar Water Authority (ZAWA): Zanzibar, Tanzania, 2017.
21. The Government of the United Republic of Tanzania. *The Water Supply and Sanitation Act*; The Government Printer: Dodoma, Tanzania, 2009.
22. Clean Drinking. Available online: <https://www.giz.de/en/mediacenter/44092.html> (accessed on 27 May 2020).
23. Mohammed, S.M. A review of water quality and pollution studies in Tanzania. *AMBIO A J. Hum. Environ.* **2002**, *31*, 617–620. [[CrossRef](#)]
24. Ndé-Tchoupé, A.I.; Crane, R.A.; Mwakabona, H.T.; Noubactep, C.; Njau, K.N. Technologies for Decentralized Fluoride Removal: Testing Metallic Iron-based Filters. *Water* **2015**, *7*, 6750–6774. [[CrossRef](#)]
25. Lilje, J.; Mosler, H.-J. Continuation of Health Behaviors: Psychosocial Factors Sustaining Drinking Water Chlorination in a Longitudinal Study from Chad. *Sustainability* **2016**, *8*, 1149. [[CrossRef](#)]

26. Antia, D. Desalination of Groundwater and Impoundments using Nano-Zero Valent Iron, n-Fe<sub>0</sub>. *Meteorol. Hydrol. Water Manag.* **2015**, *3*, 21–38. [[CrossRef](#)]
27. Antia, D.D.J. Desalination of Water Using ZVI (Fe<sub>0</sub>). *Water* **2015**, *7*, 3671–3831. [[CrossRef](#)]
28. Antia, D.D.J. ZVI (Fe<sub>0</sub>) Desalination: Stability of Product Water. *Resources* **2016**, *5*, 15. [[CrossRef](#)]
29. Marteleira, R.; Niza, S. Does rainwater harvesting pay? Water–energy nexus assessment as a tool to achieve sustainability in water management. *J. Water Clim. Chang.* **2017**, *9*, 480–489. [[CrossRef](#)]
30. Mohammed, R.; Scholz, M. Critical review of salinity intrusion in rivers and estuaries. *J. Water Clim. Chang.* **2017**, *9*, 1–16. [[CrossRef](#)]
31. Ali, Z.P.; Rwiza, M.J. Assessment of the impact of groundwater pumpage on water supply sustainability in Zanzibar, Tanzania. *Environ. Earth Sci.* **2020**, *79*, 1–15. [[CrossRef](#)]
32. Davis, F. *An Elementary Handbook on Potable Water*; Silver, Burdett & Company: New York, MA, USA, 1891.
33. Mbilinyi, B.; Tumbo, S.; Mahoo, H.; Senkondo, E.; Hatibu, N. Indigenous knowledge as decision support tool in rainwater harvesting. *Phys. Chem. Earth Parts A/B/C* **2005**, *30*, 792–798. [[CrossRef](#)]
34. Ndé-Tchoupé, A.I.; Tepong-Tsindé, R.; Lufingo, M.; Pembe-Ali, Z.; Lugodisha, I.; Mureth, R.I.; Nkinda, M.; Marwa, J.; Gwenzi, W.; Mwamila, T.B.; et al. White Teeth and Healthy Skeletons for All: The Path to Universal Fluoride-Free Drinking Water in Tanzania. *Water* **2019**, *11*, 131. [[CrossRef](#)]
35. Johnson, J. *A Groundwater Review, Zanzibar Island [Tanzania]*; FAO: Rome, Italy, 1977.
36. Lugomela, C.; Wallberg, P.; Nielsen, T.G. Plankton composition and cycling of carbon during the rainy season in a tropical coastal ecosystem, Zanzibar, Tanzania. *J. Plankton Res.* **2001**, *23*, 1121–1136. [[CrossRef](#)]
37. Saha, A.K.; Saha, S.; Sadle, J.; Jiang, J.; Ross, M.S.; Price, R.M.; Sternberg, L.S.L.O.; Wendelberger, K.S. Sea level rise and South Florida coastal forests. *Clim. Chang.* **2011**, *107*, 81–108. [[CrossRef](#)]
38. Werner, A.D.; Bakker, M.; Post, V.E.; Vandenbohede, A.; Lu, C.; Ataie-Ashtiani, B.; Simmons, C.T.; Barry, D. Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Adv. Water Resour.* **2013**, *51*, 3–26. [[CrossRef](#)]
39. Gwenzi, W.; Nyamadzawo, G. Hydrological Impacts of Urbanization and Urban Roof Water Harvesting in Water-limited Catchments: A Review. *Environ. Process.* **2014**, *1*, 573–593. [[CrossRef](#)]
40. Comte, J.-C.; Cassidy, R.; Obando, J.; Robins, N.; Ibrahim, K.; Melchioly, S.; Mjemah, I.; Shauri, H.; Bourhane, A.; Mohamed, I.; et al. Challenges in groundwater resource management in coastal aquifers of East Africa: Investigations and lessons learnt in the Comoros Islands, Kenya and Tanzania. *J. Hydrol. Reg. Stud.* **2016**, *5*, 179–199. [[CrossRef](#)]
41. Audru, J.-C.; Bitri, A.; Desprats, J.-F.; Dominique, P.; Eucher, G.; Hachim, S.; Jossot, O.; Mathon, C.; Nédellec, J.-L.; Sabourault, P.; et al. Major natural hazards in a tropical volcanic island: A review for Mayotte Island, Comoros archipelago, Indian Ocean. *Eng. Geol.* **2010**, *114*, 364–381. [[CrossRef](#)]
42. Sanchez-Moreno, J.F.; Mannaerts, C.M.; Jetten, V. Rainfall erosivity mapping for Santiago Island, Cape Verde. *Geoderma* **2014**, *217–218*, 74–82. [[CrossRef](#)]
43. Bremer, L.L.; DeMaagd, N.; Wada, C.A.; Burnett, K.M. Priority watershed management areas for groundwater recharge and drinking water protection: A case study from Hawai'i Island. *J. Environ. Manag.* **2021**, *286*, 111622. [[CrossRef](#)] [[PubMed](#)]
44. Shuler, C.; Brewington, L.; El-Kadi, A.I. A participatory approach to assessing groundwater recharge under future climate and land-cover scenarios, Tutuila, American Samoa. *J. Hydrol. Reg. Stud.* **2021**, *34*, 100785. [[CrossRef](#)]
45. Vogel, J.R.; Moore, T.L. Urban stormwater characterization, control, and treatment. *Water Environ. Res.* **2019**, *91*, 1034–1060. [[CrossRef](#)] [[PubMed](#)]
46. Nganyanyuka, K.O. Seeing Like a Citizen: Access to Water in Urban and Rural Tanzania. Ph.D. Thesis, University of Twente, Enschede, The Netherlands, 2017.
47. Ndomba, P.M.; Wambura, F.J. Reliability of rainwater harvesting systems in suburbs. A case study of Changanyikeni in Dar es Salaam, Tanzania. *Nile Basin Water Sci. Eng.* **2010**, *3*, 72–85.
48. Rai, R.K.; Neupane, K.R.; Bajracharya, R.M.; Dahal, N.; Shrestha, S.; Devkota, K. Economics of climate adaptive water management practices in Nepal. *Heliyon* **2019**, *5*, e01668. [[CrossRef](#)]
49. Marandu, S.; Chanda, O.; Kandiero, T.; Jallow, S.; Negatu, G. *Zanzibar Urban Water and Sanitation Project: Appraisal Report*; African Development Fund: Nairobi, Kenya, 2012.
50. Hussain, F.; Wu, R.-S.; Abbas, T.; Hussain, R. Rainwater Harvesting Potential and Utilization for Artificial Recharge of Groundwater Using Recharge Wells. *Processes* **2019**, *7*, 623. [[CrossRef](#)]
51. Mwamila, T.B.; Han, M.Y.; Kim, T.-I.; Ndomba, P.M. Tackling rainwater shortages during dry seasons using a socio-technical operational strategy. *Water Supply* **2015**, *15*, 974–980. [[CrossRef](#)]
52. Mwamila, T.B.; Han, M.Y.; Kum, S. Sustainability evaluation of a primary school rainwater demonstration project in Tanzania. *J. Water Sanit. Hyg. Dev.* **2016**, *6*, 447–455. [[CrossRef](#)]
53. Mwamila, T.B.; Han, M.Y.; Ndomba, P.M.; Katambara, Z. Performance evaluation of rainwater harvesting system and strategy for dry season challenge. *Water Pract. Technol.* **2016**, *11*, 829–837. [[CrossRef](#)]
54. Mwamila, T.; Katambara, Z.; Han, M.Y. Strategies for Household Water Supply Improvement with Rainwater Harvesting. *J. Geosci. Environ. Prot.* **2016**, *4*, 146–158. [[CrossRef](#)]
55. Ministry of Water and Livestock Development. *The Tanzania National Water Policy*; Ministry of Water and Livestock Development: Dar es Salaam, Tanzania, 2002; pp. 1–49.

56. Appelo, C.A.J.; Postma, D. *Geochemistry, Groundwater and Pollution*, 2nd ed.; CRC Press: London, UK, 2005; p. 683. [[CrossRef](#)]
57. Rahman, M.A.; Wiegand, B.A.; Badruzzaman, A.B.M.; Ptak, T. Hydrogeological analysis of the upper Dupi Tila Aquifer, towards the implementation of a managed aquifer-recharge project in Dhaka City, Bangladesh. *Hydrogeol. J.* **2013**, *21*, 1071–1089. [[CrossRef](#)]
58. Devonshire, E. The purification of water by means of metallic iron. *J. Frankl. Inst.* **1890**, *129*, 449–461. [[CrossRef](#)]
59. Lauderdale, R.A.; Emmons, A.H. A Method for Decontaminating Small Volumes of Radioactive Water. *J. Am. Water Work. Assoc.* **1951**, *43*, 326–331. [[CrossRef](#)]
60. Mwakabona, H.T.; Ndé-Tchoupé, A.I.; Njau, K.N.; Noubactep, C.; Wydra, K.D. Metallic iron for safe drinking water provision: Considering a lost knowledge. *Water Res.* **2017**, *117*, 127–142. [[CrossRef](#)]
61. Banerji, T.; Chaudhari, S. A Cost-Effective Technology for Arsenic Removal: Case Study of Zerovalent Iron-Based IIT Bombay Arsenic Filter in West Bengal. In *Water and Sanitation in the New Millennium*; Springer Science and Business Media LLC: Heidelberg, Germany; New York, NY, USA, 2017; pp. 127–137.
62. Naseri, E.; Ndé-Tchoupé, A.I.; Mwakabona, H.T.; Nansau-Njiki, C.P.; Noubactep, C.; Njau, K.N.; Wydra, K.D. Making Fe<sub>0</sub>-Based Filters a Universal Solution for Safe Drinking Water Provision. *Sustainability* **2017**, *9*, 1224. [[CrossRef](#)]
63. Lufingo, M.; Ndé-Tchoupé, A.I.; Hu, R.; Njau, K.N.; Noubactep, C. A Novel and Facile Method to Characterize the Suitability of Metallic Iron for Water Treatment. *Water* **2019**, *11*, 2465. [[CrossRef](#)]
64. Lufingo, M. Investigation of Metallic Iron for Water Defluoridation. Master's Thesis, Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania, 2019.
65. Noubactep, C.; Schöner, A.; Wofo, P. Metallic Iron Filters for Universal Access to Safe Drinking Water. *CLEAN Soil Air Water* **2009**, *37*, 930–937. [[CrossRef](#)]
66. Noubactep, C.; Schöner, A. Metallic iron: Dawn of a new era of drinking water treatment research? *Fresenius Environ. Bull.* **2010**, *19*, 1661–1668.
67. Noubactep, C. Metallic Iron (Fe<sub>0</sub>) Provide Possible Solution to Universal Safe Drinking Water Provision. *J. Water Technol. Treat. Methods* **2018**, *1*. [[CrossRef](#)]
68. Nansau-Njiki, C.P.; Gwenzi, W.; Pengou, M.; Rahman, M.A.; Noubactep, C. Fe<sup>0</sup>/H<sub>2</sub>O Filtration Systems for Decentralized Safe Drinking Water: Where to from Here? *Water* **2019**, *11*, 429. [[CrossRef](#)]
69. Hu, R.; Gwenzi, W.; Sipowo-Tala, V.R.; Noubactep, C. Water Treatment Using Metallic Iron: A Tutorial Review. *Processes* **2019**, *7*, 622. [[CrossRef](#)]
70. Hu, R.; Yang, H.; Tao, R.; Cui, X.; Xiao, M.; Amoah, B.K.; Cao, V.; Lufingo, M.; Soppa-Sangue, N.P.; Ndé-Tchoupé, A.I.; et al. Metallic Iron for Environmental Remediation: Starting an Overdue Progress in Knowledge. *Water* **2020**, *12*, 641. [[CrossRef](#)]
71. Van Craenenbroeck, W. Easton & Anderson and the water supply of Antwerp (Belgium). *Ind. Archaeol. Rev.* **1998**, *20*, 105–116. [[CrossRef](#)]
72. Antia, D. *Water Treatment and Desalination Using the Eco-Materials n-Fe<sub>0</sub> (ZVI), n-Fe<sub>3</sub>O<sub>4</sub>, n-Fe<sub>x</sub>O<sub>y</sub>H<sub>z</sub> [mH<sub>2</sub>O], and n-Fe<sub>x</sub> [Cation] nO<sub>y</sub>H<sub>z</sub> [Anion] m [rH<sub>2</sub>O]*; Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications; Springer Nature: Cham, Switzerland, 2020.
73. Cao, V.; Yang, H.; Ndé-Tchoupé, A.I.; Hu, R.; Gwenzi, W.; Noubactep, C. Tracing the Scientific History of Fe<sup>0</sup>-Based Environmental Remediation Prior to the Advent of Permeable Reactive Barriers. *Processes* **2020**, *8*, 977. [[CrossRef](#)]
74. Ministry of Water and Irrigation. *The Water Sector Status Report*; Ministry of Water and Irrigation: Dar es Salaam, Tanzania, 2009.
75. Ndé-Tchoupé, A.I.; Hu, R.; Gwenzi, W.; Nassi, A.; Noubactep, C. Characterizing the Reactivity of Metallic Iron for Water Treatment: H<sub>2</sub> Evolution in H<sub>2</sub>SO<sub>4</sub> and Uranium Removal Efficiency. *Water* **2020**, *12*, 1523. [[CrossRef](#)]
76. Iiliffe, J.; Iiliffe, A. *Tanganyika under German Rule 1905–1912*; Cambridge University Press: Cambridge, UK, 1969; Volume 10.
77. Halvorson, S.J.; Wescoat, J.L. Guarding the Sons of Empire: Military–State–Society Relations in Water, Sanitation and Health Programs of mid-19th-Century India. *Water* **2020**, *12*, 429. [[CrossRef](#)]
78. Gwenzi, W.; Chaukura, N.; Noubactep, C.; Mukome, F.N. Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. *J. Environ. Manag.* **2017**, *197*, 732–749. [[CrossRef](#)]
79. Roy, B.; Hartigan, J. Empowering the Rural Poor to Develop Themselves: The Barefoot Approach (Innovations Case Narrative: Barefoot College of Tilonia). *Innov. Technol. Gov. Glob.* **2008**, *3*, 67–93. [[CrossRef](#)]
80. Yannopoulos, S.; Antoniou, G.; Kaiafa-Saropoulou, M.; Angelakis, A.N. Historical development of rainwater harvesting and use in Hellas: A preliminary review. *Water Supply* **2016**, *17*, 1022–1034. [[CrossRef](#)]
81. Yannopoulos, S.; Giannopoulou, I.; Kaiafa-Saropoulou, M. Investigation of the Current Situation and Prospects for the Development of Rainwater Harvesting as a Tool to Confront Water Scarcity Worldwide. *Water* **2019**, *11*, 2168. [[CrossRef](#)]