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Qi, Qinwen

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Making Rainwater Harvesting a Key Solution for Water Management: The Universality of the Kilimanjaro Concept

Qinwen Qi [1], Janeth Marwa [2], Tulinave Burton Mwamila [3], Willis Gwenzi [4,*] and Chicgoua Noubactep [5,6,*]

1 College of International Languages and Cultures of Hohai University, Fo Cheng Xi Road 8, Nanjing 211100, China; qqw@hhu.edu.cn
2 Department of Humanities, Governance, and Leadership, Nelson Mandela African Institution of Science and Technology, Arusha P.O. Box 447, Tanzania; janeth.marwa@nm-aist.ac.tz
3 Department of Water Resources and Irrigation Engineering, Water Institute, Dar es Salaam P.O. Box 35059, Tanzania; mtulinave@gmail.com
4 Biosystems and Environmental Engineering Research Group, Department of Soil Science and Agricultural Engineering, Faculty of Agriculture, University of Zimbabwe, Mount Pleasant, Harare P.O. Box MP167, Zimbabwe
5 School of Earth Science and Engineering, Hohai University, Fo Cheng Xi Road 8, Nanjing 211100, China
6 Department of Applied Geology, Universität Göttingen, Goldschmidtstraße 3, D-37077 Göttingen, Germany
* Correspondence: wgwenzi@yahoo.co.uk or wgwenzi@agric.uz.ac.zw (W.G.); cnoubac@gwdg.de (C.N.)

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Abstract: Rainwater is conventionally perceived as an alternative drinking water source, mostly needed to meet water demand under particular circumstances, including under semi-arid conditions and on small islands. More recently, rainwater has been identified as a potential source of clean drinking water in cases where groundwater sources contain high concentrations of toxic geogenic contaminants. Specifically, this approach motivated the introduction of the Kilimanjaro Concept (KC) to supply fluoride-free water to the population of the East African Rift Valley (EARV). Clean harvested rainwater can either be used directly as a source of drinking water or blended with polluted natural water to meet drinking water guidelines. Current efforts towards the implementation of the KC in the EARV are demonstrating that harvesting rainwater is a potential universal solution to cover ever-increasing water demands while limiting adverse environmental impacts such as groundwater depletion and flooding. Indeed, all surface and subsurface water resources are replenished by precipitation (dew, hail, rain, and snow), with rainfall being the main source and major component of the hydrological cycle. Thus, rainwater harvesting systems entailing carefully harvesting, storing, and transporting rainwater are suitable solutions for water supply as long as rain falls on earth. Besides its direct use, rainwater can be infiltrating into the subsurface when and where it falls, thereby increasing aquifer recharge while minimizing soil erosion and limiting floods. The present paper presents an extension of the original KC by incorporating Chinese experience to demonstrate the universal applicability of the KC for water management, including the provision of clean water for decentralized communities.

Keywords: drinking water; rainwater harvesting; recharge pits; recharge ponds; stormwater management

1. Introduction

Climate change, population growth, and rapid industrialization are regarded as the three main global drivers increasing stresses on safe drinking water supply worldwide [1–13]. Drinking water supply has two main challenging aspects: water quantity and water quality. These two aspects have shaped the current paradigm of water management, including drinking water supply since the 1850s [2,14,15]. For any considered population (e.g., rural or urban communities), there are three predominant scenarios pertaining to drinking water provision: (i) clean water sources are locally available to quantitatively cover the needs, (ii) available water is polluted and should be treated (including blended) before supply, and (iii) drinking water is introduced from distant locations (e.g. bottled, piped or tanked water). As a result, there is a 170-year-expertise on drinking water provision including; treatment, storage, conservation and transportation over long distances. In these efforts, rainwater (RW) has been used only in some specific situations as it was considered that storing it for dry periods would be challenging [16]. However, especially for drinking water purposes, packaging rainwater can be regarded as an efficient storing tool [12].

The three main water sources are [9,16,17]: (i) groundwater (e.g., springs, wells), (ii) rainwater (e.g., dew, hail, rain, and snow), and (iii) surface water (e.g., a lake, ocean, pond, river, stream). A rule of thumb on water quality is that surface water is polluted by pathogenic microbes (first killer), while groundwater is mostly free from pathogens, but is only occasionally polluted by some inorganic chemicals of which arsenic, fluoride, and uranium are the three most widespread toxic geogenic contaminants (the three other killers). On the contrary, rainwater is usually free from geogenic chemicals while the extent of anthropogenic contamination can be regarded as low or even very low. Like surface water, rainwater will be contaminated by pathogens if it is not well-protected (e.g., packaging). The Kilimanjaro Concept (KC), is a recent concept developed to address the human health risks associated with high concentrations of fluoride in groundwater in the East African Rift Valley [18–20].

In summary, the original KC entails harvesting rainwater from pristine hilly areas (e.g., Kilimanjaro mountains) and storing it for drinking water supply. Depending on the quality of the rainwater, it can either be supplied directly without treatment or subjected to low-cost treatment in cases of contamination. In some cases, the rainwater can also be blended with groundwater to dilute contaminants to concentrations within the guideline limits for drinking water. A vital premise of the Kilimanjaro Concept is that rainwater is either free of both pathogens and chemical contaminants, or where pathogens and anthropogenic contaminants exceeding drinking water guidelines occur in harvested RW, they can be removed by simple, affordable and efficient methods like metallic iron (Fe^0) amended slow sand filters (Fe^0 SSF). In other words, RW is a relatively clean source of water that can be easily and locally made safe for drinking.

Moreover, packaging rainwater during the rainy season is an under-utilized tool to store drinking water to cater for dry periods. The KC was initially developed to address the problem of high fluoride in groundwater in Tanzania. However, due to its flexibility and adaptability, scope exists to extend it to other countries in Africa and elsewhere with similar problems. In this regard, the KC can be adapted to regions in Asia and South America, where high concentrations of geogenic contaminants (e.g., As, F, U) in drinking water pose severe human health risks [21].

The presentation until now recalls that RW is an excellent source of drinking water. However, this relatively abundant and readily available water source has initially been neglected because of the expected massive demand in storing capacity [1,16,17]. The Water Vision 2025 [22] shows that the low water utilization and under-development in Africa are not due to lack of water resources, but instead, lack of financing and technology to develop the water resources. This is evidenced by low water withdrawals for significant water uses for agriculture, community water supply, and industry, which account for just 0.7% and 3.8% of rainfall and internal renewable water resources, respectively. Technical advances during the past two centuries coupled with recent research for improved access to safe drinking water in low-income communities (decentralized systems) and efforts to rapidly transport urban runoff away from cities to prevent flooding suggest that harvested RW has the potential to provide the highest drinking water quality to a larger population [12,23–25]. Moreover, in addition to using it as a direct source of drinking water, the harvested rainwater can be locally infiltrating into the sub-surface in the form of artificial recharge to increase groundwater storage in aquifers [7,26–28]. Locally infiltrating rainwater prevents salt intrusion in coastal areas, and deeper groundwater drawdown and depletion, which are the most widely reported adverse impacts of excessive groundwater abstraction [9,28,29]. Additionally, compared to surface runoff in rivers and streams, locally infiltrated rainwater is less likely to come in contact with agriculture and industry-related pollution, mainly where agricultural and industrial wastewaters are not treated before discharge into the environment [30–33].

In summary, proper rainwater management includes: (i) storing and eventually conserving/treating RW for potable and non-potable purposes, and (ii) infiltrating the rainwater to enhance groundwater recharge. Properly infiltrating rainwater is a powerful tool to alleviate soil erosion and decrease the severity of flooding events. In non-inhabited areas, rainwater management (e.g., harvesting, infiltration, and storage) can also be universally adopted as a counter-measure against climate change. In the developed world, there are highly integrated water management systems encompassing millions of kilometers of pipes to achieve the following: (i) deliver drinking water to users at homes or in the industry, and (ii) transport wastewater away from human settlements to wastewater treatment plants [2,14,15,24,25,34–36]. The present communication presents a modification of this infrastructure to cope with changing anthropogenic pollution inputs and impacts of climate change on global water supply. A key advantage of this approach is a limited energy requirement for water treatment associated with conventional technologies.

2. Overview of Rainwater Harvesting Systems

2.1. The Status of Rainwater Harvesting Systems

In the late 1880s, Parkes [16] summarized the value of rainwater as a source of supply as follows: (i) its general good quality and great aeration make it both healthy and pleasant, (ii) the greatest benefits occur when rainwater is used for drinking water supply instead of spring or well water, which is often largely impregnated with salts, and (iii) in cases of cholera, rainwater is less likely to become contaminated with sewage than wells or springs. This aptly shows that, 132 years ago, the suitability of RW for drinking purposes was recognized. The main problem was how to store the amount necessary to supply a community for months. The idea herein is to store for later use, and also infiltrate to minimize flooding and erosion while promoting groundwater recharge.

2.2. The History of Storage Capacity or Rainwater Reservoirs

The use of rainwater storage systems is not a new concept. In ancient times, it was customary to state the capacity of rainwater reservoirs in days' consumption [17]. Many semi-empirical relations are available for this purpose. For instance, if a reservoir is designed with a 100 days' capacity, it holds enough water to cover the water demand of a community for 100 days, at a mean rate of consumption without any additional water source [17]. As an example, the following empirical formula by Thomas Hawksley was largely used for determining the reservoir capacity (C) when the mean rainfall is known:

$$C = 100/(r)^{1/2} \quad (1)$$

where r = average rainwater through three consecutive dry years. Although the rationale for this formula is not addressed herein, it is essential to note that some 120 years ago, engineers have satisfactorily sized water reservoirs of capacity of up to 250 days' supply. More importantly, RW for a whole year water supply (250 days = 8 months) was already commonplace [16,17]. Today, more simple approaches to estimate the capacity of RWH reservoirs are available, depending on the intended uses of the harvested water [19,23,37]. It is evident that the total capacity needed herein may be higher, as water is harvested also to be artificially infiltrated. Appropriate temporary storage before subsequent infiltration is critical to avoid contamination of rainwater. The storage capacity does not only depend on direct uses in households nor on the irregularity of rainfall, but on the target amount of water to be harvested for immediate direct use and infiltration into groundwater systems for subsequent use during the dry season [28,30]. This approach would be an apparent attempt to realize an old vision of King Parakramabahu of Sri Lanka (12th century), who stated that, “Let no drop of water flow to the sea unused by man” [4]. The next section gives an overview of the status of RWH in Kenya with a particular focus on the design of the African Water Bank which is regarded as proof that the KC is immediately applicable.

2.3. Kenyan Progress in RWH

The practice of rainwater harvesting (RWH) is an under-utilized tool for water management [3,18,19]. In the East African Rift Valley and Kenya in particular, RWH is mainly used for drinking water and agricultural needs [23,38]. It has been recognized that RWH reduces stormwater runoff, decreases watershed pollution, and improves water management in an affordable manner [23,28,30,38–42]. Harvested rainwater is currently utilized for: (i) drinking water supply, (ii) domestic non-potable uses such as toilet flushing and clothes washing, and (iii) landscape irrigation and agricultural crop irrigation [43,44]. The current trend is to improve rainwater harvesting strategies [23,38,40–42,44].

Kenya is a very water-stressed country, as two-thirds of the land is arid or semi-arid [23,42]. The quest for a sustainable solution to water scarcity has driven significant innovations in RWH [23,42,45]. The potential of RWH to alleviate water shortages has been assessed using scientific tools [42,45]. Recently, the African Water Bank (AWB), an international non-governmental organization (NGO), has committed to harvest and store rainwater on a large scale. In this regard, the collection area is enhanced; the guttering system and storage systems are increased, filters, water gauges, and first flush devices are optimized [23].

A typical AWB rainwater harvesting system collects 400 to 450 m^3 of rainwater within some three hours of steady rain. The collection area is an artificial roof of 900 to 1600 m^2. Storage tanks of various capacities are designed and constructed. The largest tank ever constructed in Narok County has a capacity of 600 m^3 and can be expanded [23]. Calculations showed that 600 m^3 of water could serve a community of 400 people for approximately two years (24 months) without any extra rain. The capacity can be increased at a rate of 220 m^3 per year. The AWB rainwater harvesting system is affordable and easy to maintain locally in a self-reliant manner. It also uses local skills, labor, materials, and technology [23]. This corresponds to the vision of the Kilimanjaro Concept [18–20], which is now to be extended to incorporate Chinese experience, mainly for distant water transfer. A key advantage of the KC is that urban slums and rural areas are served as well.

It should be anticipated that, in the extension of the Kilimanjaro Concept, RWH tanks and infiltration ponds for individual households will be sized depending on their needs and the volume of water falling (to infiltrate). More importantly, community storage tanks should be designed to ensure that “no drop of water flow to the sea unused by man” [4]. That is, they should be large enough to contain excess rainwater from individual compounds.

3. The extended Kilimanjaro Concept

3.1. Overview of the Kilimanjaro Concept

The Kilimanjaro Concept advocates for the creation of a regional network to harvest, store and subsequently use rainwater from rooftops and other clean surfaces such as non-inhabited mountainous areas (i.e., catchments) for safe drinking water supply. This choice is motivated by the well-documented quality of rainwater and the relative ease to technically remove its typical contaminants using affordable, applicable and efficient chemical-free technologies [18,19]. Typical contaminants occurring in rainwater, and the factors influencing rainwater quality are discussed in detail in earlier papers [46,47]. In summary, depending on roof materials, land use, climatic factors and storage conditions, rainwater may contain contaminants such as trace metals, pathogenic organisms, and physical objects (e.g., leaves, bird and animal droppings) [31,32,46–48]. Thus preliminary analysis and subsequent treatment using low-cost methods may need to be considered on a case-by-case basis. Recently, some studies have investigated the following: (i) surface treatments for enhancing rainwater harvesting [30], (ii) site selection for rainwater harvesting and subsequent storage systems [32], and (iii) the effects of climate change and variability on urban rainwater harvesting systems [33]. These recent studies provide critical information for the implementation of the Kilimanjaro Concept. The extended Kilimanjaro Concept, presented herein, adds the following components: (i) the collection of stormwater for non-potable uses, (ii) the local creation of infiltration ponds for artificial recharge of the groundwater systems, and (iii) based on Chinese experience, the long-distance conveyance of water from rural areas to serve urban populations in demand. This approach will help individual communities to become self-reliant in water supply or at least reduces dependence on imported water or/and groundwater withdrawals. Moreover, by installing groundwater recharge ponds at a local level, groundwater recharge is increased while flood control is improved. Additionally, some communities will occasionally export excess rainwater to nearby communities in need.

The Kilimanjaro Concept is not primarily a tool to serve water-scarce communities, but rather an approach to potentially achieve the following: (i) for long-term environmental conservation (alleviating erosion), and (ii) mitigate the impacts of droughts and floods under climate change conditions [49]. Accordingly, the concept extends beyond avoiding desalination or diversifying water supply sources, but seeks to harness a still neglected natural resource, and regards rainwater and stormwater in an old perspective [4,14,16,50–52]. In fact, this perspective has historically preceded centralized water supply systems, which often exclude highly dispersed and vulnerable communities in most low-income countries [14].

Indeed, several opportunities have been realized in water harvesting, with roads and grazing areas being considered as potential water harvesting catchments. The traditional perception is that roads once constructed would change the surface hydrology and impacts on runoff, often causing local flooding, waterlogging and erosion. However, work by Steenbergen [53] on Ethiopian roads has recommended that this can be turned in the enormous potential for water harvesting and management. Also, Grum et al. [54] have reported that it is possible to harvest the concentrated water on roads for multiple purposes including groundwater recharge, soil moisture replenishment and storage for domestic and animal uses in dry periods. The runoff water can be harvested from culverts, side drains and depressions into converted borrow pits, infiltration ponds, and swallows, while in some cases water can be spread from the road surface and gullies plugged to enhance recharge [55,56]. Such water can be used to support livelihood activities such as household food and livestock production, an aspect constituting an extension of the KC beyond drinking water. In this regard, the KC is an opportunity for improving integrated water resources management, including safe drinking water supply and managed aquifer recharge (MAR) [25,26,50,51,56,57], and provision of water for household food and nutritional security. The concept is not only for low-income communities or semi-arid areas but is generic, thus can be extended to other environmental settings whether they face limited clean water supply or not.

3.2. Ideal Rainwater Catchments for the Kilimanjaro Concept

Catchment characteristics, including area, and nature of materials and potential for contamination are critical in the KC. The following catchments may be ideal for the KC:

(i) Water from mountain (seasonal) streams flowing over clear, stony uncontaminated surfaces without either cultivation, pastoral activities or habitations on the sides, should be chemically analyzed for hardness and separately stored,
(ii) Runoff water flowing over an uncultivated surface and a non-inhabited hill or mountain should be chemical analyzed and separately stored,
(iii) Rooftop rainwater should be collected and stored separately to be mainly used for drinking water purposes,
(iv) Road runoff water could serve as water sources for agricultural practices, but its quality will need to be monitored for chemical parameters.

3.3. Upland Surface and Groundwater Sources

Clean water from groundwater sources (e.g., springs) and surface water (streams, runoff, rivers) from pristine areas can also be harvested to supplement rainwater and stormwater. All mountain water is of this nature, and so is the water of such valleys as their steep slopes do not often allow cultivation or development of human settlements. Moreover, all water from entirely uninhabited tracts of land such as natural woodlands may also be considered under this category. Such water is a very common source of drinking water supply, and includes mountain streams originating from high land (e.g., the Kilimanjaro Mountains). The water of this class is sometimes very potable, although the quality varies considerably among areas. In some cases, 'peatiness', characterized by a brown color, is a property of water from many mountainous and moorland areas. However, compared to pathogenic and toxic geogenic contaminants, such peatiness, when occurring to a moderate extent, does not often pose human health risks.

3.4. Lessons from China

The East African Rift Valley and portions of China have in common high fluoride concentrations in groundwater sources, a feature that has shaped the authorship of the present communication. The first two peer-reviewed communications presenting the Kilimanjaro Concept have clearly stated that people should be ready to accept long-distance water piping systems [18,19]. The premise of this section is that the expertise for long-distance water transport is mostly available in China [6,8,29,58–60], and could just be adapted to the needs of the EARV regions. On the other hand, China can base its drinking water supply in fluoride-polluted areas on the KC and use the extended KC for groundwater recharge in the whole country. Currently, Chinese rural areas with fluoride-polluted water sources rely on the use of specific engineered adsorbents for water treatment [6,8,61,62]. Such treatment methods have inherently low fluoride removal efficiency and are comparatively expensive [18,19,63]. Therefore, the KC developed initially for EARV can be extended by drawing lessons from water supply systems in China. It should be explicitly stated that this communication is not reporting on the state-of-the-art water supply in China. There are excellent review articles on various aspects [29,59,61]. The focus is on aspects that can facilitate the implementation of the KC, mainly: (i) long-distance water transfer and (ii) water quality management.

3.4.1. Routinely Controlling Water Quality

In China, rural water supplies are supervised by the Ministry of Water Resources, while urban water supplies are supervised by the Ministry of Housing and Urban-Rural Construction. The National Health Committee routinely inspects the water quality both in rural and urban areas [8]. In the EARV regions and sub-Saharan-Africa (SSA) in general, although standards exist, accredited laboratories to monitor the quality of drinking water are very limited [64,65]. Monitoring water quality is the cornerstone for safe drinking water provision [64–68]. In this regard, communities in SSA including the EARV can learn lessons on drinking water quality monitoring and system maintenance from their Chinese counterparts.

3.4.2. Integrating Urban and Rural Water Supplies

China has widely solved water supply shortages in rural areas near cities/towns by an integrated urban-rural water supply [8]. In this approach, urban water supply systems are expanded to rural areas by pipe networks [69,70]. Provinces such as Guangdong, Jiangsu and Jiangxi have largely used this approach to supply rural residents [8,69,70]. For example, Peng and Ye [69] reported on a pipe network extended over 1683.04 km and supplying 22 villages with a total population of 315,900 inhabitants in the countryside area surrounding the city of Ezhou. A total of eleven (11) waterworks secure water supply in the named rural areas.

The main concern with the urban-rural water supply approach is water quality stability in the distribution systems [8]. Due to the long distance to rural consumers, the water retention time in pipelines is long. The comparatively lower water consumption in rural areas is also a design concern in particular concerning the low residual disinfectant doses, and water quality deterioration arising from bacteria regrowth and corrosion of piping material. However, the cases drawn from China demonstrate that long-distance transport of water between urban and rural communities is feasible. However, whereas in China water is transported from urban to rural areas, the Kilimanjaro Concept basically reverses the trend by "exporting" excess rural water to cities where there is often high demand, thus, inherently solving this problem. For low-income communities, the extended Kilimanjaro Concept should strive for a disinfectant-free water supply. This is because, chlorination, which is widely recommended by the WHO is not really affordable, and reacts with organic matter in water to form trihalomethanes, which are carcinogenic [71,72]. In cases, where contamination of rainwater with pathogenic microbes is expected or suspected, stored water can be intermittently heated (e.g., once per week) to about 80 degrees and kept for some 10 minutes at this temperature (pasteurization). In such cases, intelligent heating systems can also be considered for this purpose, using solar energy or wood from short growth cycle plant species with good calorific properties. To avoid excessive costs, such pasteurization should only be applied at local treatment plants to a fraction of the stored rainwater ready for supply. At individual rural households, solar disinfection (SODIS) of quantities sufficient for drinking consumption can be promoted, with better models of SODIS established.

3.5. Universalizing the KC: The Role of Water Storage Systems

Although the KC was originally developed for Kilimanjaro in Africa, this communication argues that the elements of the concept can be adapted to various settings (i.e., universalizing the KC). In this regard, the components of the KC can be modified or improved to provide clean drinking water under diverse socio-economic and biophysical conditions. The KC entails harvesting rainwater compound per compound, village per village, and hill per hill. Designing water harvesting systems ensures that excess water from each compound would flow directly to the next local storage station, which may include a low-cost water treatment system. In this regard, water storage systems are a critical component of the KC since they provide a buffer against the high temporal variability associated with rainwater and stormwater availability. Depending on location conditions, both surface and underground storage systems can be used. In the context of the KC, rainwater or stormwater can also be harvested and stored in individual surface storage systems (Figure 1) or a cascade of inter-connected groundwater storage reservoirs (Figure 2), which then supply water to a water treatment and storage facility. In mountainous areas, such as the Kilimanjaro Mountains, such storage systems can be located in hilly areas upstream of the water treatment and storage systems and communities to facilitate low-cost water conveyance by gravity. Overall, the Kilimanjaro Concept advocates for the storage, protection (from contaminant, light, and oxygen) and redistribution of readily available water, but mostly rainwater.

Depending on local conditions, a number of groundwater storage systems are envisaged. First, in cases where the risk of contamination by geogenic and anthropogenic pollutants is minimal, the harvested rainwater can be stored in natural aquifers, which will act as *de facto* groundwater storage systems for drinking water provision. Such systems will be analogous to artificial groundwater recharge, which is meant to replenish groundwater resources [28]. Second, contaminated stormwater can be passed through natural aquifers to achieve partial removal of contaminants in stormwater. This process, often known as soil aquifer treatment (SAT), has been used to treat wastewater before its subsequent injection into groundwater systems and use for irrigation. Depending on the quality of the groundwater from the SAT systems, such water can be used for non-potable purposes or subjected to low-cost treatment and used to supplement clean rainwater. Compared to surface storage systems, properly designed and sited underground natural aquifer systems may also have other advantages, including: (i) reducing the cost associated with artificial storage systems, (ii) reduces water loss via evaporation, and (iii) less prone to contamination by pollutants in surface runoff.

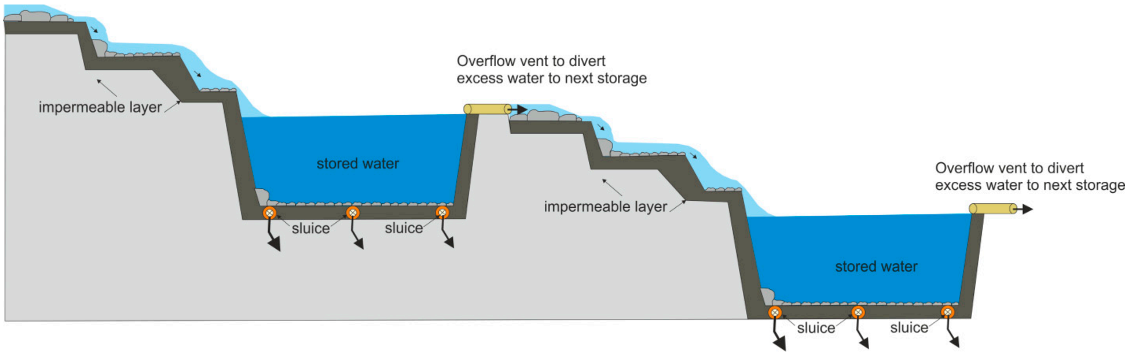

Figure 1. A conceptual depiction of a groundwater system for the collection and storage of rainwater/stormwater.

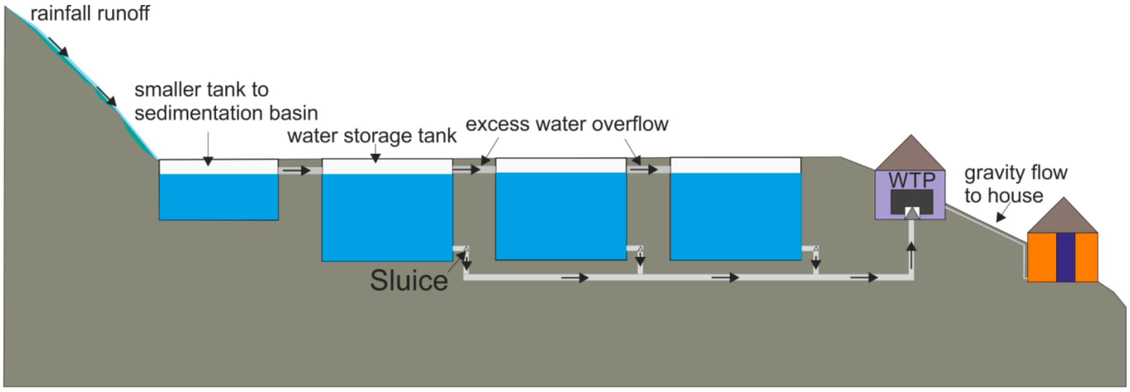

Figure 2. A cascade of an inter-connected system for the storage of harvested rainwater/stormwater.

The harvesting and storage of both rainwater and stormwater enable the subsequent conjunctive use of both water resources. On the one hand, subject to its quality, clean rainwater can be used for drinking water provision in its raw state or after affordable treatment [72–75]. On the other hand, stormwater, which is likely to be contaminated by anthropogenic pollutants, can be used for livestock watering and irrigation of household nutritional and herbal gardens [76]. Livestock, and household nutritional and herbal gardens play a critical role in food, income, and nutritional security in Africa and other developing countries. In this regard, the KC provides scope to address the water-food nexus in Africa and other developing countries. The water-food nexus entails that water and food problems in most developing countries, including those in Africa co-exist, thus are better addressed simultaneously. In fact, the capacity of stormwater harvesting systems with storage components to mitigate the adverse effects of droughts and mid-season dry spells caused by climate change and variability in agro-ecosystems is well-documented in Africa. Here, the KC proposes that such systems can be extended to clean water provision for drinking purposes. Lessons drawn from China indicate that the harvested rainwater can be transported from areas with excess water to those in need, an aspect which is currently overlooked in drinking water provision in Africa.

3.6. The Kilimanjaro Concept Versus Borehole-Based Drinking Water Supplies

In developing countries, low-income households lack access to centralized drinking water supplies, which are often unreliable and expensive. In such cases, communities often rely on surface water sources or shallow groundwater wells, which are prone to anthropogenic pollution. In most informal settlements in urban and peri-urban areas, such drinking water sources are often in close proximity with on-site sanitation systems such as pit latrines and septic tanks. The current approach to clean water provision in such settings is to drill deep boreholes because groundwater from such boreholes is considered less prone to anthropogenic pollution. However, in the case of the East African Rift Valley System and other regions in Asia and South America, such groundwater contains high concentrations of toxic geogenic contaminants (As, F, U). In such instances, attempts to provide drinking water to such communities by drilling boreholes expose communities to serious health risks [77]. In fact, it is such settings that motivated the Kilimanjaro Concept. Table 1 presents a comparative summary highlighting the novelty and potential benefits of the Kilimanjaro Concept versus the traditional approach to drinking water provision based on borehole drilling.

Table 1. A summary comparison of the potential benefits of the Kilimanjaro Concept versus the current borehole-based drinking water supplies.

Kilimanjaro Concept	Borehole-based drinking water systems
(1) Safeguards populations against geogenic pollution	(1) Exposes populations to geogenic pollution
(2) Harvested rainwater is analyzed, and treated if needed (e.g., using low-cost Fe^0 filters).	(2) In cases of geogenic pollution, treatment methods are rarely ineffective, but always expensive
(3) Harvested rainwater also recharges groundwater.	(3) Excessive groundwater abstraction causes borehole failure and groundwater depletion.
(4) In coastal areas, artificial recharge prevents saltwater intrusion.	(4) In coastal areas, intensive groundwater withdrawal promotes saltwater intrusion
(5) Flexible and adaptable to various conditions, including catchment types (roofs, roads, mountainous areas), and can be used either as a substitute or supplement for conventional water sources.	(5) High yield aquifers only occur in certain geological formations and localities, which may not coincide with human settlements.
(6) RWH combined with artificial infiltration attenuates flood risks by reducing Hortonian runoff volumes, peak flows, and erosion.	(6) No capacity to attenuate floods.
(7) Affordable RWH systems can be developed at household level, promoting ownership and control.	(7) Installation costs for boreholes are often prohibitive especially for small communities.

In the discourse on rainwater harvesting systems for drinking water provision, including the KC, some critics often highlight that the cost of such systems is quite high. In cases where communities have no access to centralized water systems, and groundwater is contaminated with highly toxic geogenic contaminants, the issue of perceived 'high cost' should be cast in a proper context. In the authors' view, the 'high cost' should only be with respect to other competing options that will provide clean water without exposing communities to even more serious health risks. Moreover, given that rainwater harvesting for drinking purposes has a long history [18,19], and can be practiced with locally-made devices, one even wonders whether the cost for such systems is as high as often perceived. Thus whether the KC is more expensive than the conventional drinking water supply systems can only be determined during a detailed design process, which can only be done on a case-by-case basis.

In summary, the novelty of the KC relative to the dominant approach based on drilling boreholes for drinking water provision includes the following aspects:

(1) It addresses water quality aspects (e.g., toxic geogenic contaminants) and associated human health risks,
(2) It reduces the risk of saltwater intrusion, and groundwater depletion, and in some cases may even enhance groundwater recharge,
(3) Can be coupled to household food production, income and nutritional security thus addressing the water-food nexus especially in Africa,
(4) The use of gravity-driven systems and low-cost water treatment systems may reduce the risk of frequent failure associated with boreholes, and
(5) It is flexible and amenable to universal application, suggesting that it can be adapted to various local conditions.

3.7. Shaping the Future of the Kilimanjaro Concept

There is still much to be considered to make RWH a first-line agent in the global battle for integrated water management. The primary objective of this communication was to show the non-inferiority of RW as a drinking water source with respect to the initial quality and the extent of treatment needed. Once the non-inferiority of rainwater as drinking water source is ultimately established, the superiority of local infiltration for groundwater recharge will be considered. The extended Kilimanjaro Concept, on the other hand, is seeking the long-term management of water resources irrespective of any changing climatic phenomenon, including disproportionate distribution of rainfall.

The extended Kilimanjaro Concept also addresses rural/urban disparity. Urban areas in the developing world are increasingly subject to the scarcity of drinking water due to the following: (i) uncontrolled influx of rural populations, (ii) lack of technical and management capacity, and (iii) inadequate water distribution system [12]. Since water is managed on a large-scale basis (e.g., regional), water properly infiltrated in a village is available in the next city depending on the topography and aquifer connectivity. Additionally, urban households are aware that RWH is not a low-value alternative for drinking water supply and non-potable uses. Traditionally, urban populations adopt several strategies to cope with shortages in water supply. These strategies include drilling wells, storing water, buying bottled water and collecting water from alternative sources [12,78].

The initial uptake and adoption of the KC are likely to be rapid and more widespread under certain preconditions, which will also determine the sustainability of the rainwater harvesting systems. These preconditions include:

(1) Local need and commitment to harvest rainwater driven by a critical lack of clean drinking water. Examples include, (i) high geogenic contaminants in existing drinking water sources, and (ii) lack of access to decentralized water systems as is the case in most developing countries,
(2) Local positive experience in rainwater harvesting and its benefits, even without the influence of agents such as local extensionists and NGOs. For example, in Uganda and Sri Lanka households are reported to use simple devices such as banana leaves or stems as gutters to harvest up to 200 liters of water from large trees in a single rainstorm [79],
(3) Frequent failure of traditional drinking water sources such as boreholes, and piped water supply systems due to increasing water demands, and variability of water availability,
(4) The potential for rainwater harvesting systems to create co-benefits through multiple uses, including household food production, domestic uses and income generation,
(5) Climatic conditions characterized high variability of rainfall, surface, and groundwater. In this regard, dry and wet tropical climates with short dry seasons and multiple high-intensity rainstorms may provide ideal conditions for water harvesting. In such cases, rainwater harvesting systems can be used to bridge water shortages during the dry season,
(6) Demonstrated technical, financial and socio-economic feasibility, including local technical capacity, community involvement and stakeholder participation including women empowerment.

4. Conclusions and Outlook

This current communication extends the Kilimanjaro Concept initially developed to overcome the human health risks associated with high concentrations of toxic geogenic contaminants in groundwater. It is further argued that the KC could be a universal solution for clean water provision for communities lacking access to centralized conventional water treatment systems. Specifically, the following were highlighted: (i) based on lessons drawn from China, excess rainwater in storage facilities can be transported even over long distances to communities in need using conveyance systems, (ii) besides harvesting rainwater solely for drinking water provision, the KC may also include runoff harvesting for non-potable uses, including food production, and (iii) in cases where the risk of geogenic pollution is low, stormwater and runoff can be collected and artificially recharged into groundwater system for subsequent use during the dry season. These features overcome some of the limitations associated with conventional rainwater harvesting. This makes the KC adaptable to various conditions, thus provides a potential solution for decentralized clean water provision. However, the detailed design of the system and the cost of implementing the KC will need to be estimated on a case-by-case basis. Overall, the KC concept seeks to promote the use of rainwater where and when it falls, while minimizing contamination. Moreover, scope exists to couple the KC to food production at household level, thereby addressing the water-food nexus in developing countries. The concept represents a shift from the current approach to clean water provision, which has been dominated by drilling and installation of boreholes, with limited consideration of the water quality aspects. Such an approach has often failed to overcome the human health risks associated with toxic geogenic contaminants in drinking water. To demonstrate feasibility of the KC, the next phase of the research should entail pilot-testing the concept at key selected sites. Such pilot studies should include detailed design and analysis, and socio-economic and financial evaluation of the concept versus other competing options such as centralized drinking water systems and groundwater-based water supply systems.

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