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Roof-Harvested Rainwater Use in Household Agriculture: Contributions to the Sustainable Development Goals

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Abstract: Food and water are at the heart of sustainable development. Roof-harvested rainwater kept in rainwater storage systems (RSS) and used in household agriculture (HA) has the potential to increase yields and supplement household nutrition. Combined systems may contribute to at least eight of the United Nations' 17 Sustainable Development Goals (SDGs). In this paper, a daily analysis tool, ERain, is used to assess what area of vegetables can be reliably irrigated by roof-harvested rainwater. A socio-economic context is built around an orphanage in the semi-humid region of Nakuru, Kenya. Comparisons are made with the semi-arid region of East Pokot. A 225 kL closed masonry tank and a 1 ML open reservoir with an additional 8 kL/day of recycled water entering are analyzed for various roof sizes. The 225 kL RSS connected to 1000 m^2 of roof and irrigating 1000 m^2 could increase yields from 1850 to 4200 kg/year in Nakuru. If evaporation was controlled, the 1 mL RSS and recycled water system could support 4000 m^2 of land, yielding nearly 20,000 kg/year, which is enough to meet the WHO recommended vegetable dietary requirements of the orphanage. A combination of crops, some for consumption and some for sale, could be grown.

Keywords: sustainable development goals; rainwater harvesting; rainwater storage systems; agricultural water use from harvested rainwater; household agriculture; urban agriculture; village; Kenya

1. Introduction

The Garden of Eden, or Paradise, has long captured the heart and imagination. Many aspire to live in, and search for, such a paradise lost, often for more ascetic reasons. The Paradise of Eden, however, is described as not only beautiful, but also providing abundant food and being amidst a great river system, supplied with ample water (Genesis 1:11, 2:10). Gardening as an activity is known to be good for both physical and mental health [1], but the capacity for increasing household nutrition should not be overlooked. Yields from between zero (crop failure) to over 20 kg of vegetables per m^2 have been reported for small-scale agriculture [2]. This is particularly important in developing countries, where many people lack nutrition. Food and water are, and always have been, at the heart of a sustainable environment. Fifty years have passed since man landed on the moon (16 July 1969), but the challenge of providing what the moon cannot, food and water, remains. Zero hunger worldwide is a worthy, but historically unrealized, dream. The fact is that more than enough food is produced worldwide to feed everyone [3]. However, it is unevenly distributed, leading to a world where 1 in 9 people remain hungry and 1 in 4 children are stunted [4], while 1.9 billion adults are overweight [5]. A report by the UN indicates that the food demand will double by 2050 [6], whilst others suggest that it may only need to increase by 25%–75% [7]. If there is not enough food produced and distributed, the situation will only get worse. The problem is multidimensional, and there is a call for innovative systems and holistic approaches that build upon traditional knowledge and cultural preferences whilst also protecting the environment. Household agriculture (HA) or home gardening at a small scale bypasses the distribution issue and has the potential to significantly contribute to household nutrition, particularly that of women and children.

Rainfed agriculture alone, particularly in arid or semi-arid regions, often proves to be unreliable and insufficient [8] and an adequate water supply is essential to achieving such yields. However, with the already increasing concerns about water security and increased competition over fresh water resources [9], where will the additional water come from? Modern building techniques favor impermeable surfaces, such as concrete driveways and roof coverings. The often negative effect of “paving paradise” [10] that includes the pollution of waterways and flooding, if overcome, could potentially mean that this approach could be used to provide the additional water sought for small-scale irrigation of household agriculture (HA). Roof-covered areas are particularly suitable for rainwater storage systems (RSS), harvesting the water before it becomes polluted by ground surfaces. The increased use of metal roofs over traditional grass roofs etc. in developing countries [11] means that more dwellings are becoming suitable for rainwater collection. In developing countries, RSS shows potential to support small-scale agriculture and in turn, to help provide important nutrition [12,13], while also saving water [14,15]. To demonstrate the potential, consider a 100 m^2 roof used exclusively for HA in a semi-arid region with a mean annual rainfall (MAR) of 400 mm; if connected to a garden of the same size, the rainfall available would then double (800 mm). In practice, water is lost to deep percolation and surface runoff and the effective rainfall, at 70% of the total rainfall [16], would only be 280 mm. An appropriately designed RSS system in this scenario could have a considerable impact on the yield. If the rainwater is polluted, e.g., from the collection system or air pollution, then it may not be the preferred source for drinking and potable uses [17], but agricultural use is still acceptable. The non-uniform distribution of rainfall in arid and semi-arid regions causes droughts that are often the cause of crop failure [18], making the use of RSS and irrigation particularly advantageous. The focus region of this study, Nakuru, Kenya [19], is one such region.

Recent examples of RSS use in HA or home gardening include Australia’s “Water Smart Gardens and Homes Rebate Scheme” rebate scheme, specifically designed to encourage people to install rainwater storage systems (RSS) for household gardens and reduce pressure on the reticulated supply [20]. There have been a number of projects promoting small-scale agriculture and it is also becoming increasingly popular in developing countries [21]. Chip Morgan, through the Africa Water Bank (AWB), has been installing 225 kL tanks in Kenya that are claimed to be able to irrigate 1350 m^2 greenhouses and grow vegetables to make a profit [22]. The original concept of a project in Lesotho, South Africa, included the construction of 4 kL RSS to supplement the gray water being used in the garden [23]. Another project, under the “Food for Assets” incentive, was quite successful in Lesotho, South Africa, with over 23,000 keyhole gardens being constructed between 2006 and 2013 [24]. This kind of small-scale agriculture can also help to maintain “forgotten varieties” [25] and enhance biodiversity. This paper is applicable to all forms of small-scale agriculture and the term HA is intended to include community- or village-scale agriculture used for the owners and so may also be applicable to community gardens and allotments [26,27].

The purpose of this paper is to fill the current knowledge gaps in RSS-based HA. There is a lack of detailed analysis of RSS capacity with respect to evapotranspiration and the irrigation water demand at the HA scale and the capacity of RSS to meet that demand [28]. In particular, the aim is to determine what land area can be irrigated and what potential crop yield can be obtained from a given combination of HA area and RSS. ERain, a daily water balance analysis tool, is designed to analyze combined HA and RSS using daily climate data. For a realistic context, the study is based on conditions at Miti Mingi ("Many Trees") Village in Nakuru, Kenya, an established orphanage that can house 120 children and 45 adults. This enables direct feedback on the results and the discussion includes insights about the practicality of the solution. A community's acceptance of a system and their preferences will have a direct impact on the design and hence the analysis and results. Community engagement is often neglected in more technical research papers and so its importance and impact are highlighted here. It is expected that the findings of this study will both be of assistance to the village and relevant to community- and school-size projects internationally. It is expected to be a key reference for NGOs, environmentalists, researchers, town planners, water engineers, governments, and policy makers considering the use of HA and RSS in addressing the relevant sustainable development goals in various international contexts.

2. Materials and Methods

Climate data was analyzed using ERain, a daily analysis tool first described in Amos et. al. [28–30], and which has now been updated to include evapotranspiration calculation. The main elements of ERain are a Yield-After-Spillage RSS analysis of daily rainfall data, and an analysis of daily climate data to calculate agricultural water use using FAO 56 and the crop yield in response to water availability using FAO 33. The method employed in ERain was preferred over other tools available as it includes an analysis of not only rainfall data, but also climate data. Models that come from the agricultural sector have been found not to include a water tank balance model [28]. For example, Cropwat uses monthly data for its calculations and does not include a tank balance model [31]. Aquacrop, which in many respects supersedes Cropwat, although it is a good model for crop water use, also does not include a tank balance model [32]. Conversely, tools that focus on rainwater harvesting and domestic water use regularly include a daily time step analysis of tank balance, but do not include a detailed analysis of evapotranspiration and crop water use [31]. For example, AQUACYCLE [33,34] and Urban Volume and Quality (UVQ) [35,36] do not include any detailed analyses of crop water use. The data requirements and a more detailed description of the method employed in ERain follow.

2.1. Data

2.1.1. Study Site

Two regions of Kenya are considered in this study: Nakuru and East Poket. According to the agro-climatic zone map of Kenya [37], Nakuru is in zone III-5. The moisture zone (III) is thus semi-humid, with a rainfall value of 800–1400 mm/year and an Eo (annual average potential evaporation) of 1450–2200 mm/year (calculated using Penman's equation), with a high to medium potential for crop growth and a fairly low (5%–10%) risk of failure of an adapted maize crop. The temperature zone (5) is considered cool-temperate, with a very rare incident of frost, and is considered to include lower highlands with an altitude of 1850–2150 m. East Poket, in comparison, is in zone V-2. The moisture zone (V) is thus semi-arid, with a medium to low potential for crop growth and a high risk of failure of an adapted maize crop. The temperature zone (2) is considered warm, with no incident of frost, and includes midlands. Further comparisons are detailed in Table 1.

Table 1. Agro-climatic zone definitions for selected locations.

Location	Moisture Zone	Rainfall mm/year	[1] Eo mm/year	Crop Growth Potential	[2] Crop Failure	Temp Zone	Temp Mean Annual °C	Temp Mean Max. °C	Temp Mean Min. °C	Incident of Frost	Altitude
Nakuru	semi-humid	800–1400	1450–2200	high to medium	fairly low 5%–10%	cool-temperate	16–18	22–24	10–12	very rare	1850–2150
East Poket	semi-arid	450–900	1650–2300	medium to low	high 25%–75%	warm	22–24	28–30	16–18	none	900–1200

[1] annual average potential evaporation; [2] failure of an adapted maize crop.

2.1.2. Climate Data

Developments in the satellite estimation of rainfall data and climate data mean that analysis can be undertaken in areas where there is little or no recorded ground data available [38–41]. Much of Kenya has limited climate data, so daily agroclimatology data were obtained from the NASA Langley Research Center POWER Project [42] for the Miti Mingi Village, Nakuru, Kenya, which has a latitude of −0.3534, longitude of 36.1628, and elevation of 2179 m. The data includes the following:

- Maximum temperature in °C;
- Minimum temperature in °C;
- Dew point temperature in °C;
- Wind run in m/s;
- Solar radiation in MJ/m^2/day;
- Rainfall in mm/day.

The relative humidity needed for the FAO 56 calculations was calculated from the max., min., and dew point temperature. The data were analyzed and compared (Figure 1) with averages for the closest station, Nakuru Airfield (lat. of 0.3, long. of 36.15) obtained from CLIMWAT [43] and the World Meteorological Organization (WMO) [44]. Rainfall data for the area from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) data sets [45,46] was ultimately preferred to the NASA rainfall data for reasons explained under data integrity in the results section. Due to the lack of availability of alternative daily climate data, the NASA data was still used for temperature, wind, and solar exposure, while both NASA and CHIRPS data were used for precipitation for comparison.

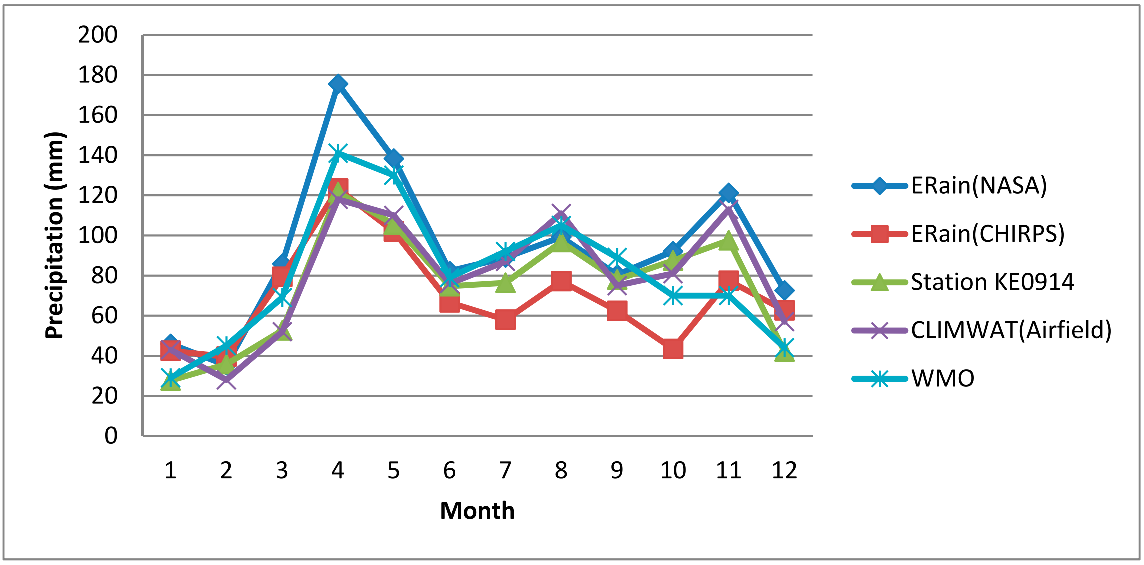

Figure 1. Comparison of monthly precipitation for Nakuru from various sources.

2.1.3. Yield, Water Use, and Nutritional Need

An average amount of vegetables that can be produced of 7.3 kg/m^2/year. was chosen, based on a study of 2608 mixed stand communities or home food gardens [2], assuming three crops per year. The study does, however, report a massive variety in yields, from 0.44 up to 22 kg. This agrees quite well with the findings of Foeken, Owuor [47] in Nakuru, who found a range of 0.22 to 20.17 kg, so crop failure should also be considered (Table 2). Importantly, they found a correlation between plot size and yield. The smaller plots generally had a higher productivity. This is because they are generally close to living quarters and thus get frequent attention and more personal care. It is not unreasonable to think that they are also better watered, in which case the water supply would also be a contributing factor to the higher yields. Under this hypothesis, if water could be supplied domestically for irrigation, then larger areas of land could realize a higher yield.

Table 2. Yield comparisons for various plot sizes.

Location	Statistic	Plot Size (m^2)	Yield (kg/m^2/year)	Area (m^2) Req to Provide 1 Person [3]
Nakuru, Kenya [1]	mean	<10	20.17	7
Nakuru, Kenya [1]	mean	10–99	4.73	31
Nakuru, Kenya [1]	mean	100–999	0.51	286
Nakuru, Kenya [1]	mean	1000+	0.22	664
Nakuru, Kenya [1]	mean	All	0.31	471
New Jersey, USA [2]	Max.	Mixed stand	21.97	7
New Jersey, USA [2]	Upper	Mixed stand	6.35	23
New Jersey, USA [2]	Lower	Mixed stand	0.98	149
New Jersey, USA [2]	Min.	Mixed stand	0.44	332
New Jersey, USA [2]	mode	Mixed stand	7.32	20
Any location	Failure	All	0	-

[1] Source: Foeken, Owuor [47]; [2] Source: Rabin, Zinati [2], assuming three harvests per year; [3] Based on the WHO recommendation of 400 g/p/d (146 kg/p/y) of fruit and vegetables.

Water use is determined based on the methods employed in FAO 56 [48], and an average crop coefficient value (Kcb) of 1 is assumed for general vegetables. This study is only indicative, and plantings may vary somewhat from the averages used here. Evapotranspiration inside the greenhouse is taken as a conservative 0.75 times that outside, towards the upper limit given in Carolina and Eduardo [49]. Scenarios for both greenhouses and open gardens were considered. It was assumed that no rain falls directly on the land inside the greenhouse. Values for daily fruit and vegetable consumption were taken as those advised by the World Health Organization (WHO), at 400 g per adult per day and 200 g for smaller children [50]. This can be compared to the Australian Government's National Health and Medical Research Council (NHMRC) guidelines [51]. NHMRC's serving size is 75 g [52], and up to six servings of vegetables or 450 g/p/d for an adult. Assuming a ratio of three 80 g servings of vegetables to two of fruit, the WHO recommendation is 240 g of vegetables. This is considerably less than the NHMRC's 450 g, and this is partly because the WHO recommendation excludes starchy vegetables, such as potatoes and cassava, while NHMRC does not. These differences should be noted; however, for simplicity, in this study, we have compared the results to $\frac{1}{4}$ of the WHO amount of 400 g as it is expected that the garden will only be used to supplement household supplies. It is also assumed that some of the crop yield could also include fruits, such as strawberries, and possibly fruit trees. For comparison, 400 g/d equates to 146 kg/year, and at the chosen rate of 7.32 kg/m^2/year, this equates to 20 m^2 of growing area, which agrees with Iannotti [53], who suggests that at intermediate yields, 18.5 m^2 is required to supply vegetables and soft fruits for an individual. If the yields in Table 2 could be realized, then an area of 10 m^2 would be sufficient for an individual, although variety may be an issue.

2.1.4. Scenario

Information about the circumstances at the orphanage were obtained from discussions with Sotheycan (Treadwell, Chittenden 2019), a charitable organization that promotes the principle that education is the best route to sustainable change [54], and with the onsite Program Manager/Village Director, James Wabara (2019). The orphanage houses 120 children and 45 adults.

There is no reticulated water supplied to the orphanage, so water must be either sourced on site or purchased and delivered by truck at high prices. The primary water sources are therefore bore water and roof-harvested rainwater, while water is currently only purchased on rare occasions due to system failure. The bore is powered by mains electricity and yields up to 35 kL per day, which is pumped into an overhead tank. Approximately 8 kL/day of the domestic water is recycled and stored in a 1000 kL reservoir. The reservoir also has a roof catchment of 1400 m^2 flowing into it, and is analyzed both with and without the recycled water inflow to assess performance. It is uncovered and subject to evaporation losses, which are modeled at 1.05 times the daily evapotranspiration (ETo) rate based on Allen, Pereira [48], assuming that the reservoir depth is below 2 m. The evaporable surface is 20 by 25 m, or 500 m^2. A second tank of 225 kL has a roof catchment of 800 m^2 that is used to top up the overhead bore tank for domestic use if the bore fails. If both the bore and rainwater fail, water must be purchased from the local water bowser and delivered by truck at a cost of 4000 KSH (approximately AU$56) for 10 kL. In this paper, we focus on the 1000 kL reservoir, which is used to irrigate a 240 m^2 of greenhouse crops. There is 4 acres of land available that could also potentially be irrigated. Miti Mingi Village is located in a semi-humid zone. The same scenario is analyzed in East Pokot, which is a semi-arid area, for comparison. For both locations, the capacity of the 225 kL tank to support a garden was considered in more depth, as tanks this size are being installed cost effectively in Kenya by the Africa Water Bank (AWB) [22]. As the setup can vary considerably, roof catchments varying from 20 to 2000 m^2 were considered. To examine the potential garden area that can be supported by the tank, a wide variety of cultivated areas from 10 to 20,000 m^2 were analyzed.

2.2. Method

2.2.1. Tank Balance Model, Water Demand, Evapotranspiration, and Crop Yield

The performance of the RSS was analyzed using a daily time step water balance simulation model. A Yield-After-Spillage (YAS) model was preferred for the analysis as it is generally agreed to give a more conservative estimate, which is more suitable for the design in this context [55]. The YAS model described in Fewkes and Butler [56] was used.

The water demand is ultimately the evapotranspiration and this was calculated on a daily basis based on the climate data obtained from NASA. The well-known FAO Penman–Monteith equation [48] was chosen as the NASA data provides the necessary data for this calculation, with the exception of relative humidity data. The relative humidity (RH) data (minimum and maximum) was calculated from the minimum and maximum temperature and the dew point temperature, as per Eccel [57] (Equations (1)–(5)).

$$\mathrm{ea} = 0.6108 \times \exp((17.27 \times \mathrm{Tdew})/(\mathrm{Tdew} + 237.3)) \tag{1}$$

$$\mathrm{eo\_Tmax} = 0.6108 \times \exp((17.27 \times \mathrm{Tmax})/(\mathrm{Tmax} + 237.3)) \tag{2}$$

$$\mathrm{eo\_Tmin} = 0.6108 \times \exp((17.27 \times \mathrm{Tmin})/(\mathrm{Tmin} + 237.3)) \tag{3}$$

$$\mathrm{RHmin} = 100 \times \mathrm{ea}/\mathrm{eo\_Tmax} \tag{4}$$

$$\mathrm{RHmax} = 100 \times \mathrm{ea}/\mathrm{eo\_Tmin} \tag{5}$$

2.2.2. Definition of Reliability and Calculation of Crop Yield

RSS reliability is a measure of the system's ability to meet the demand. In the case of a garden, the demand is that required to maintain the vegetables' maximum evapotranspiration (ETo max) at each respective stage of development. When the soil water content is reduced below the readily available water (RAW), the plant cannot transpire at its maximum rate and the actual evapotranspiration (ETo actual) will be less than the maximum (Eto max) [48]. Etx is defined as the maximum possible Eto over the crop cycle (or plants life), assuming an unlimited water supply, while ETa is the actual total ETo over the crop cycle. Hence, ETa and ETx are accumulated over the plant's life. Reliability is then calculated as shown in Equation (6). Reliability was not calculated based on the "number of days the demand is met" for three main factors, as that would have complicated the calculation. Firstly, there will not always be a demand as the soil water storage will supply water when it is above the RAW. Secondly, when below the RAW, the plant's demand is still partly met, as ETo is reduced and not zero until the total available water (TAW) is reached. Thirdly, the soil water deficit may also be either partly or fully met on any given day, depending on the rainfall.

$$\text{Reliability} = \frac{\text{ETa}}{\text{ETx}} \tag{6}$$

The focus of this study is water use, so the maximum crop yield assumed (an annual average of 7.3 kg/m^2/year.) is reduced based on the ability of the RSS to supply the necessary irrigation water. Ultimately, this reduction was calculated using the method described in FAO 33 [58] (Equation (7)):

$$\left(1 - \frac{\text{Ya}}{\text{Yx}}\right) = \text{Ky}\left(1 - \frac{\text{ETa}}{\text{ETx}}\right)\left(1 - \frac{\text{Ya}}{\text{Yx}}\right) = \text{Ky}\left(1 - \frac{\text{ETa}}{\text{ETx}}\right), \tag{7}$$

where Ya and Yx are the actual and maximum crop yield, respectively; Ky is a yield response factor, taken as 1.1 in this analysis; and ETa and ETx are as above.

3. Results

This section presents results from the ERain analysis, proceeded by a comparison of the NASA climate data with other available data for the site.

3.1. Climate Data Integrity

The climate at NUKURU was found to be reported variously. Figure 1 shows a comparison of the average monthly precipitation according to the NASA data, CHIRPS data, CLIMWAT data, and data from a nearby rainfall station (KE0914). The MAR is given as 1116, 834, 896, and 951 mm/year, respectively.

The NASA rainfall data also seemed problematic as on closer analysis, it was found that it reported 354 days of rain per year, while the CHIRPS data reported only 57 days, which is much less than the WMO value of 132 days/year [44] for Nakuru. Excluding rain below 1 mm, the NASA data still has an average of 221 days/year. to match the CHIRPS data days of rain, and any rainfall below 5.6 mm would need to be ignored, but this would give an MAR of only 594 mm. To match the CHIRPS MAR of 834 mm/year, NASA rainfall below 3.1 mm would need to be excluded from the data, still reporting 114 days of rain, which is considerably more than the CHIRPS data, but closer to the WMO value of 132 days. Therefore, the NASA rainfall data not only varies considerably from the CHIRPS and station data in terms of annual and monthly averages, but also from the CHIRPS in terms of the daily rainfall depth. The max. daily rainfall reported by NASA is 81 mm, compared to 104 mm by CHIRPS. This is important because actual evapotranspiration will be affected by the rainfall distribution, as well as the quantity. The water balance and performance of RRS will also be affected. Where the main catchment is a relatively impervious roof, small rainfall events, e.g., in this case, considered to be below 3.1 mm or 5.9 mm, will still supply water due to the relatively low losses. Another consideration is that the grid resolution of CHIRPS data has a much finer resolution at 0.05 deg. compared to the NASA data at 0.5 deg. With these considerations, the CHIRPS rainfall data was deemed to be preferable to the NASA data. A comparison of the monthly averages calculated in ERain with the NASA data for the min./max. temperature is shown in Figure 2.

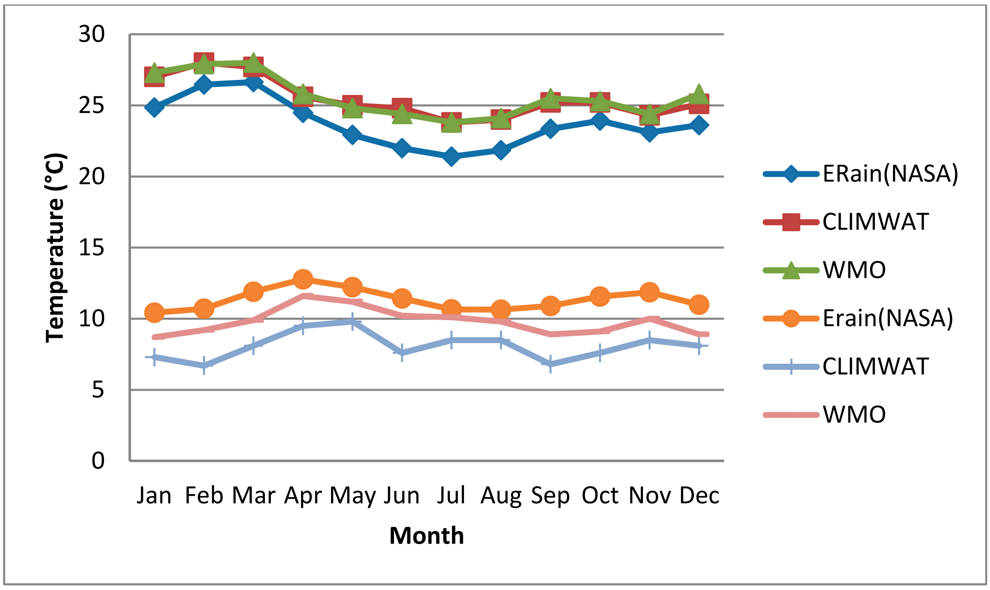

Figure 2. Comparison of monthly max./min. temperature for Nakuru from various sources.

The NASA data has a lower maximum and higher minimum temperature than most other sources report for Nakuru. Table 3 shows a comparison of average annual climate data for Nakuru.

Table 3. Comparison of annual average climate data for Nakuru from various sources.

Source	Min. Temp	Max. Temp	Humidity	Wind	Rad	ETo	Rain	Rain
	°C	°C	%	km/day	MJ/m^2/day	mm/day	mm	Days
CLIMWAT (airfield)	8.1	25.5	71	161	19.3	3.94	951	-
ERain (NASA-MMV) *	11.33	23.69	-	181	20.27	3.81	1086	363
ERain (CHIRPS-MMV) *	-	-	-	-	-	-	833	57
WMO (Nakuru)	9.8	25.6	-	-	-	-	963	132
Nakuru Lanet Police Post (KE0914)	-	-	-	-	-	-	896	-

* These values were calculated from daily data using ERain.

For solar radiation, CLIMWAT reports an average of 19.3 MJ/m^2/day, whilst NASA exhibits a slightly higher value of 20.27 MJ/m^2/day; wind is, on average, 181 km/day compared to 161 km/day, respectively. Due to the lack of availability of alternative daily climate data, the NASA data was used to calculate ETo, while both NASA and CHIRPS data were used for precipitation and compared. As can be seen in Table 3, the average annual ETo calculated from the NASA data using ERain, 3.81 mm/day, compares quite well with the CLIMWAT value of 3.94 mm/day, although it is on the low side. ETo is discussed in more detail in the next section.

3.2. ETo Analysis

Figure 3 shows monthly ETo results for Nukuru. Figure 4 shows daily ETo results from ERain, demonstrating that the calculated ETo varies from approximately 2 to 6 mm/day. The annual averages for CLIMWAT are 3.94 mm/day or 1439 mm/year; from the NASA data, this was slightly lower, at 3.81 mm/day or 1392 mm/year (Table 3), which is expected to result in a lower water use from the RSS, and hence a reduced reliability. The value given in the agro-climatic zone map of Kenya [37], 1450–2200 mm/year, is higher, but this value was Eo (annual average potential evaporation) calculated using Penman's 1948 equation for open water surfaces and it gives values higher than FAO 56's Penman–Monteith equation used here.

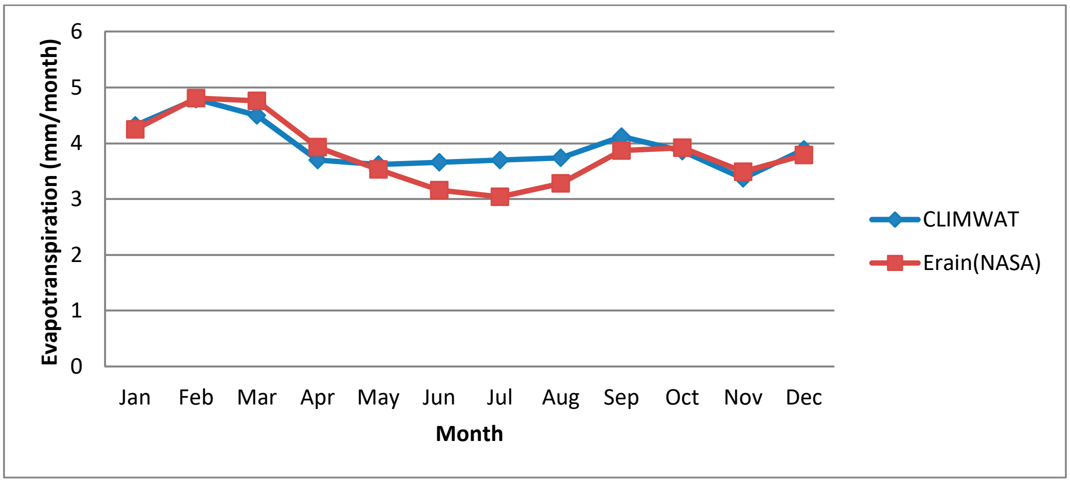

Figure 3. Monthly average evapotranspiration (ETo) for Nakuru, comparing CLIMWAT with ERain (NASA data).

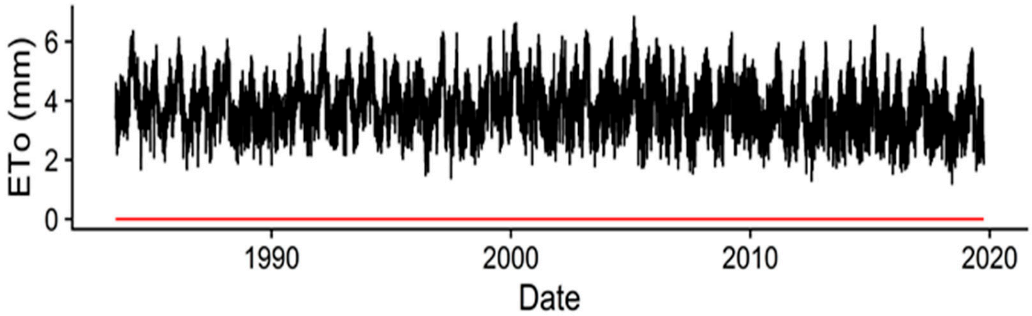

Figure 4. Daily ETo and RH results with input climate and rainfall data.

In summary, there is considerable variability in the climate data and any results should be interpreted with this in mind. The NASA data serves as an upper limit of RSS performance as it reports rainfall at the higher end of the scale, and the climate data results in an ETo at the lower end, which tends to result in a higher system reliability than might be the case. The CHIRPS rainfall data is about average, while the ETo is still based on the NASA data, so a higher ETo is possible, which implies that the results will not be conservative and should be expected to be at the mid to upper range of potential reliability. Uncorrected NASA data has been used for crop simulation modeling, with some degree of success, but correction using at least 3 years of observed data is preferred [59]. Details about the NASA data methodology can be found in Westberg, Barnett [60]. The climate may be even less favorable or more variable in the future, so any results based on historic data should be considered with a degree of uncertainty, and hence reasonable contingency plans can be developed. Nevertheless, a comparison with CLIMWAT results (Figure 3) indicates that the NASA climate data does provide a reasonable estimate of evapotranspiration and hence crop water requirements.

3.3. RSS Reliability and Crop Yield

In this section, RSS reliability is discussed, this is, the ability of the RSS to supply water to the field and maintain the maximum evapotranspiration (ETx) that the crop requires at its growth stage. It is calculated from the actual evapotranspiration (ETa) as ETa/ETx.

3.3.1. The 1 ML Reservoir in the Orphanage Scenario

Figure 5 shows a comparison of results using the NASA and CHIRPS rainfall data. ETo was calculated using the NASA data in both cases. OF represents an open field, as opposed to GH (greenhouse). In the GH, rain does not fall directly on the soil, so it relies exclusively on irrigation.

_Evap indicates that the RSS is open and subject to evaporation; otherwise, it is closed and is deemed to suffer from no evaporation loss. Rcyl indicates that the 8 kL of recycled water is included as daily inflow to the RSS, and as expected, this can support much larger areas of irrigation. RF indicates rain-fed only; in other words, it indicates how well the rainfall alone could supply the water needs all year around.

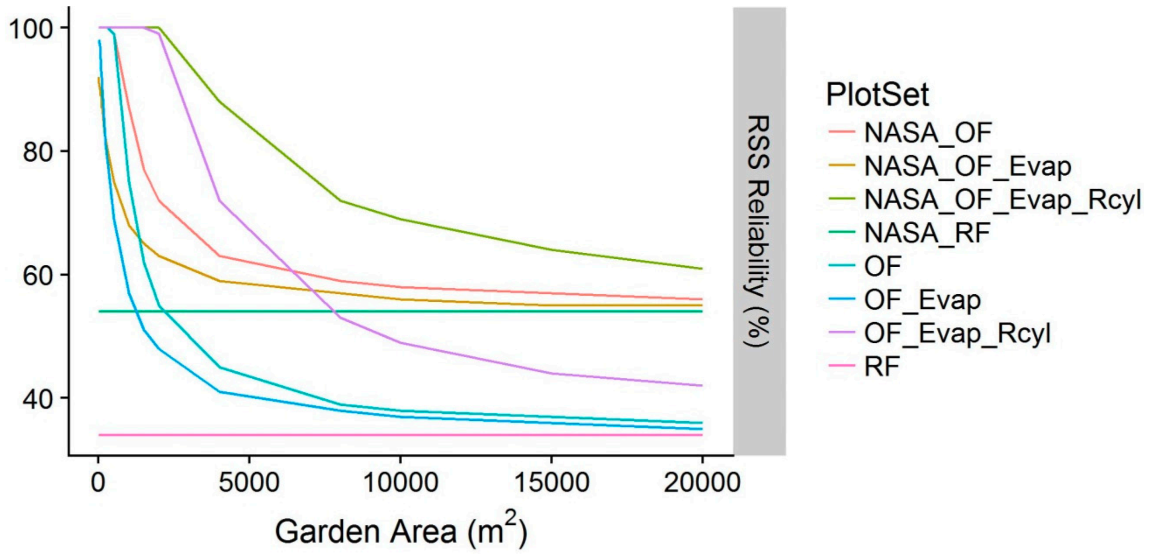

Figure 5. NASA vs. CHIRPS for various scenarios.

Comparing the NASA_RF with RF (CHIRPS-NASA), it can be seen that the former reports a reliability of 54% and the latter reports a value 20% less, at 34%. For East Poket, not shown here, the reduction was from 53% to 26%. Therefore, it appears that the NASA data shows little difference between the semi-humid region of Nakuru and the semi-arid region of Poket. The use of CHIRPS rainfall results in a more conservative estimate and we deemed the NASA data to be preferable, so the analysis from here on was conducted using a combination of CHIRPS rainfall and NASA climate data.

Figure 6 shows the CHIRPS analysis without the NASA data for a smaller range of garden areas and includes the analysis of a greenhouse (GH).

With reduced evaporation (75%), despite no rain falling directly on the soil, the performance is good while there is water available in the RSS. If the recycled water is included, about 2000 m^2 of land can be reliably irrigated and 4000 m^2 with a 72% reliability in the open field, resulting in yields of 14,330 and 19,190, respectively. This would be more than enough to supply the orphanage with the WHO required daily vegetables/fruit for approximately 100 adults, with a value of 14,600 kg/year ($0.4 \times 365.25 \times 100$). In the greenhouse scenario, the respective yields are 14,420 and 16,860. For the larger area, the greenhouse has only a 64% reliability. Once the RSS is at capacity, the greenhouse reliability reduces steeply below the RF reliability and the open field becomes preferable. With careful water management and seasonal crop plantings, however, it may still be possible to get good returns from an acre of land (4046.86 m^2), which is considerably more than the current greenhouse size of 240 m^2. However, if the recycled water is not included, and there is evaporation from the RSS (GH_Evap), then the current greenhouse could only be supported with a reliability of 80%. When the reliability is reduced, then the evaporation loss reduces as the area increases, since the RSS will be empty at times. However, if evaporation is controlled (GH), then 500 m^2 could be supported with 100% reliability, representing twice the current area. It should be noted that this is based on the average results over the years 1983 to 2017, and annual variability over this period means that, in some years, this reliability may be much lower. This, and the uncertainty of future climates, would need to be considered in any long-term planning.

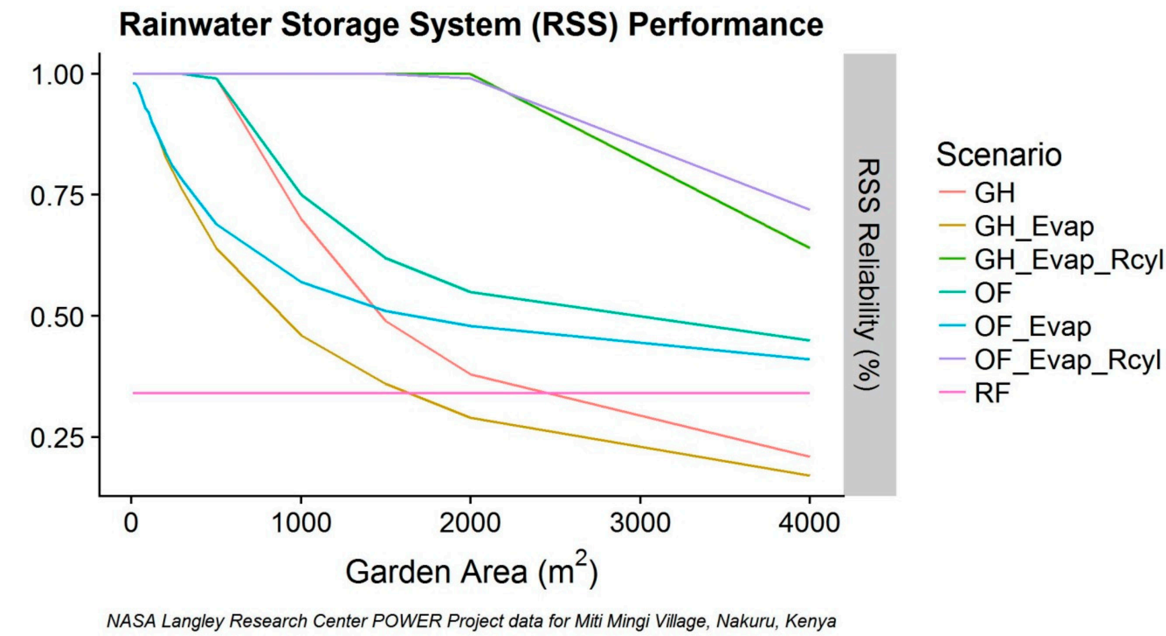

Figure 6. CHIRPS.

Table 4 shows the maximum and hypothetical actual crop for both Nakuru and East Poket under greenhouse conditions with reduced evaporation, but no rain falling on the irrigated area. The yield of 7.21 kg/m^2/y represents the maximum yield of 7.3 kg/m^2/y, and the discrepancy is because the data length does not exactly match the cropping year.

Table 4. Open 1 ML rainwater storage system (RSS) maximum, actual, and average crop yields for both Nakuru and East Poket.

Crop Area	Max. Crop Yield	Hypothetical Actual Crop Yield (Mixed Vegetables) (Total and Per m^2)							
		Nakuru (GH)		East Poket (GH)		Nakuru (GH_Evap)		East Poket (GH_Evap)	
(m^2)	(kg/y)	(kg)	(kg/m^2/y)	(kg/y)	(kg/m^2/y)	(kg/y)	(kg/m^2/y)	(kg/y)	(kg/m^2/y)
10	73	72	7.21	72	7.21	71	7.07	55	5.54
20	145	144	7.21	144	7.21	141	7.06	109	5.45
40	291	288	7.21	288	7.21	277	6.93	211	5.29
60	436	433	7.21	433	7.21	407	6.78	308	5.14
80	581	577	7.21	577	7.21	531	6.64	399	4.99
100	727	721	7.21	721	7.21	650	6.50	484	4.84
120	872	865	7.21	865	7.21	764	6.36	565	4.71
160	1163	1153	7.21	1153	7.21	968	6.05	712	4.45
200	1454	1442	7.21	1442	7.21	1154	5.77	845	4.23
240	1744	1730	7.21	1730	7.21	1320	5.50	962	4.01
300	2181	2163	7.21	2163	7.21	1545	5.15	1114	3.71
500	3634	3586	7.17	3406	6.81	2097	4.19	1485	2.97
1000	7269	4708	4.71	3453	3.45	2777	2.78	1875	1.87
1500	10,903	4587	3.06	3238	2.16	2981	1.99	1929	1.29
2000	14,537	4397	2.20	2987	1.49	2974	1.49	1822	0.91
4000	29,074	3431	0.86	1949	0.49	2202	0.55	994	0.25
8000	58,149	1361	0.17	274	0.03	564	0.07	13	0.00
10,000	72,686	655	0.07	30	0.00	171	0.02	0	0.00
15,000	109,029	32	0.00	0	0.00	0	0.00	0	0.00
20,000	145,372	0	0.00	0	0.00	0	0.00	0	0.00

The reduction in crop per m^2 (kg/m^2/y) mirrors the reliability result and under GH conditions, with evaporation from the RSS excluded, the crop reduces to 4.71 kg/m^2/y for 1000 m^2. The maximum total crop yield is 4587 kg for the 1500 m^2 area, with the crop yield being reduced to 3.06 kg/m^2. In comparison, for the semi-arid region of East Poket, the maximum yield is only 3453 kg for 1000 m^2 and increasing the area to 1500 m^2 only reduced the overall yield. If the RSS system is not closed and water is allowed to evaporate from the system (GH_Evap), then the system cannot fully support the irrigating requirements in either location. Interestingly, in this scenario, peak yields are 1500 m^2 in both Nakuru and East Poket, but at 2981 and 1929 kg/y, respectively. Although, in Nakuru, for example, for triple the area, from 500 to 1000 m^2, the yield only increased by less than half from 2097 to 2981 kg/y. Under open field conditions (OF), the crop yield does not peak, but continues to increase with area. This is because there is still 34% (Nakuru) or 26% (East Poket) reliability under rain-fed conditions (Figure 6), so any extra land will still increase the crop yield. However, in practice, this may not be viable due to the extra labor and costs involved. A system that maintains a higher reliability and value closer to the maximum yield/m^2 may be preferable. In this case, the open reservoir does not appear to be a good option, due to the excessive evaporation. Without the 8 kL daily input from the recycled water, it is unlikely that the current 1 ML reservoir could support the full irrigation needs of anything larger than a very small garden (Table 4). Therefore, closed RSS systems are preferable.

3.3.2. RSS 225 System Results

In this section, the results for a closed 225 kL RSS attached to roof sizes up to 2000 m^2 and garden areas up to 20,000 m^2 (2 Ha) are investigated. The larger roof sizes would be representative of schools, community centers, or clusters of houses. Currently, the Miti Ming Village has a total of 2400 m^2 of roof; however, 800 m^2 is connected to an RSS used to supplement the domestic bore water supply. Masonry tanks of this size are currently being constructed in Africa reasonably cost effectively, so such a system may be economically feasible. Figure 7 shows the results for both Nakuru and East Poket. The lower rows of the figure focus on smaller areas and roof sizes.

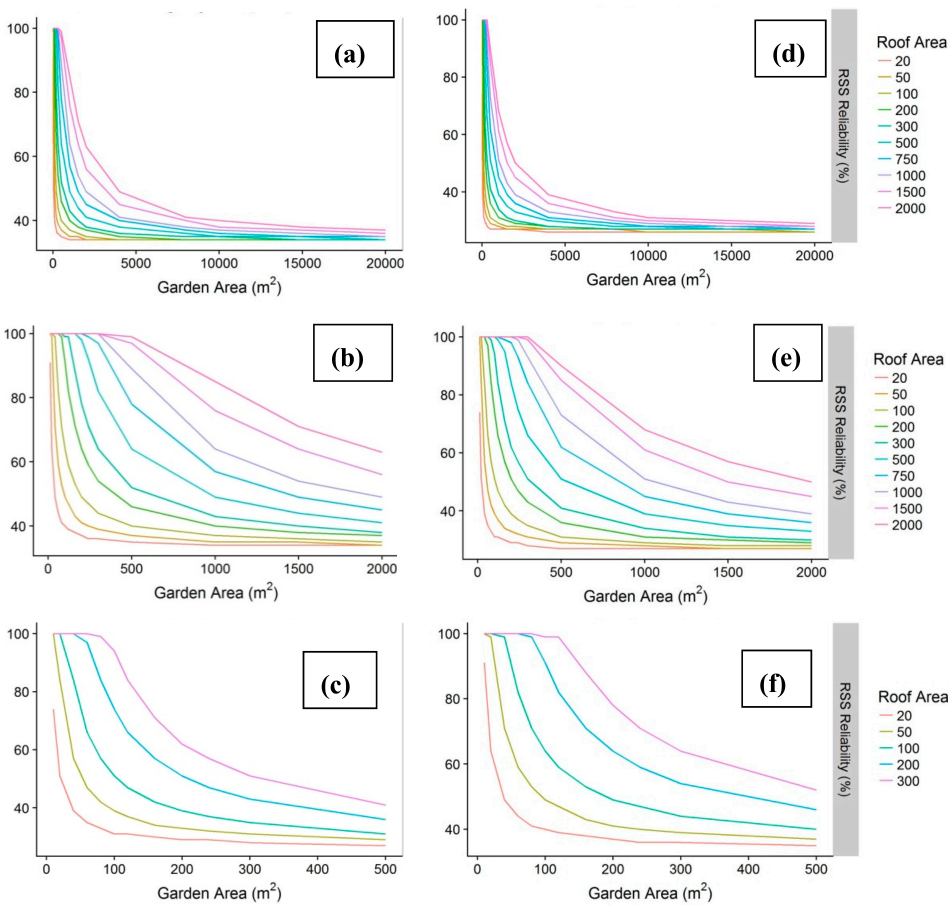

Figure 7. RSS reliability for a 225 kL tank, roof areas up to 2000 m^2, and garden areas up to 2 Ha for Nakuru (**a**–**c**) and East Poket (**d**–**f**).

As expected, semi-humid Nakuru has a greater reliability than semi-arid East Poket (Figure 7a,b). From Figure 7a,b, it can be seen that for garden areas above 5000 m^2, the reliability dropped below 50% for any roof area at either location, and although a larger roof will still offer a higher reliability, this advantage becomes negligible with the larger garden areas. With the larger roof catchments, gardens of up to 500 m^2 can be supported quite well in Nakuru, for example, 1000 m^2 of roof can still supply 90% of the water requirements. However, in East Poket, the same roof could only support about half the area. Small roof areas, such as those which might be found on an individual house, can only support small garden areas. For example, the 100 m^2 roof (e.g., 20 m by 5 m) green line (Figure 7c,f can fully support 40 m^2 of garden in Nakuru, and 20–30 m^2 in East Poket.

It should be noted, however, that the rain-fed reliability in the semi-arid region is much lower, at 26% compared to 34% (using CHIRPS data), and crop failure is more likely, so the system may still be bringing greater advantages to the semi-arid region. Table 5 shows a comparison of total crop yields for the rain-fed condition (RF) compared to having the closed 225 RRS installed for open field (OF) irrigation. The number of people that the system can support with 100 g of vegetables per day (1/4 of the WHO recommendation) is also shown. Roof areas from 500 to 2000 m^2 and garden areas from 40 to 1000 m^2 are considered. For smaller garden areas below 200 m^2, the increase in crop yields is greater in East Poket than in Nakuru, and above 300 m^2, the increase is greater in Nakuru. Presumably, this is because the system is reaching its capacity for the East Poket climate.

Table 5. 225 kL RSS crop yields for both Nakuru and East Poket.

		Nakuru (RF Reliability of 34%)				East Poket (RF Reliability of 26%)			
Roof Area (m^2)	Garden Area (m^2)	Crop Yield (kg/y)			People Supported with 100 g/day	CropYield (kg/y)			People Supported with 100 g/day
		RF	OF	Increase		RF	OF	Increase	
500	40	74	288	214	8	51	288	238	8
1000	40	74	288	214	8	51	288	238	8
1500	40	74	288	214	8	51	288	238	8
2000	40	74	288	214	8	51	288	238	8
500	100	185	721	536	20	127	719	592	20
1000	100	185	721	536	20	127	721	594	20
1500	100	185	721	536	20	127	721	594	20
2000	100	185	721	536	20	127	721	594	20
500	160	297	1149	852	31	203	1078	874	30
1000	160	297	1153	857	32	203	1154	950	32
1500	160	297	1153	857	32	203	1154	950	32
2000	160	297	1153	857	32	203	1154	950	32
500	200	371	1415	1044	39	254	1164	910	32
1000	200	371	1442	1071	39	254	1437	1183	39
1500	200	371	1442	1071	39	254	1442	1188	39
2000	200	371	1442	1071	39	254	1442	1188	39
500	300	556	1707	1150	47	381	1301	920	36
1000	300	556	2156	1599	59	381	1976	1595	54
1500	300	556	2163	1606	59	381	2124	1743	58
2000	300	556	2163	1606	59	381	2155	1774	59
500	500	927	2103	1176	58	635	1559	924	43
1000	500	927	3112	2185	85	635	2429	1794	66
1500	500	927	3496	2569	96	635	2923	2288	80
2000	500	927	3582	2655	98	635	3141	2506	86
500	1000	1854	3051	1196	84	1270	2197	927	60
1000	1000	1854	4202	2348	115	1270	3119	1849	85
1500	1000	1854	5195	3340	142	1270	3920	2650	107
2000	1000	1854	5855	4001	160	1270	4483	3213	123

For the 2000 m^2 roof, the increases in crop yield are quite large at both locations, even for the 1000 m^2 (0.1 ha, $\frac{1}{4}$ acre) garden, increasing from 1854 to 5855 kg and from 1270 to 4483 kg for Nakuru and Poket, respectively. This could supply 160 and 123 adults with $\frac{1}{4}$ of their daily vegetable requirement, which is enough to supplement a community the size of Miti Mingi Village. Even with a smaller roof area of 500 m^2 and considering the full portion of 400 g, the system could still support 21 or 15 adults, and for the $\frac{1}{4}$ portion, 84 or 60 adults, respectively. Either way, the system can substantially contribute to household or school nutrition if managed well. This shows that a 225 kL tank can potentially help produce a lot of food in semi-arid regions where there is a roof catchment available to capture the water.

4. Discussion

4.1. Lessons Learnt from Miti Mingi Village

Analysis has confirmed that there is a real potential to increase household agricultural production through rainwater harvesting and the implementation of RSS. The analysis confirms that the AWB's claims that a 225 kL tank can irrigate 1350 m^2 of greenhouse [22] are quite possible from a water perspective. RSS and HA systems could be used as income or to boost household nutrition, or probably both. Using the larger 1 ML system, the Miti Mingi Village orphanage is already practicing this to some degree and would like to increase their agricultural production. However, there are a number of constraints, including farm management. Whether for commercial purposes or household nutrition, to be successful, the system will be required, among other things, to conduct the following:

- Attain high yields;
- Practice water management;
- Plant the correct crops (for nutrition or sale);
- Result in seed saving;
- Have good pest management–currently an issue;
- Maintain fertilization and soil health;
- Conduct crop rotation.

Other technical issues can also be a problem, for example, in the first year of operation, the 1 ML reservoir leaked because of a poor quality PVC liner. If pumps are used, pump maintenance is a technical skill that needs to be learnt. Currently, farm management is an issue; if agriculture had been a stronger part of the children's education, perhaps there would now be some older students who had grown up at the orphanage who could take on a more serious farm management role and help educate the younger children. These skills could be learnt at a young age through school gardens, or involving the children in gardening activities at home, whilst simultaneously improving household nutrition. It is reasonable to think that if children build confidence in growing things, then a higher percentage will go on to successfully produce food, whether as a job or just at home. This would then have a big impact on the country in the long term. This is already being practiced at the orphanage to some degree, but there is room for improvement and there are certain barriers. One major issue is that in education in Kenya, agriculture does not form part of the school curriculum and is not examinable. This is something that should perhaps be reconsidered. In Australia, it is not directly examinable, but in NSW, it can be incorporated and is examinable where it forms part of other subjects, such as Science, and there are plenty of materials available to help with this. For example, the NSW board provides a K-6 teaching agriculture resource [61], and large agricultural organisations such as Cotton Australia provide resources that can be used in the Australian Curriculum, such as the "Farm Diaries" produced by the Primary Industries Education Foundation of Australia, which can be incorporated into Design and Technology, Science, Geography, History, and Maths, and addresses sustainability [62]. Internationally, FAO produces resources for setting up school gardens, for example, program lessons for "*Integrating agriculture and nutrition education for improved young child nutrition*" [63]. The Kenyan government school system may need to change its way of thinking for household agriculture to reach its full potential. Progress in Lesotho, South Africa, the lessons learned, the success of the "Food for Assets" incentive, and the increased interest in including agriculture in education [24] are also promising for HA implementation in Kenya.

Kenya is a water-scarce country and rainwater harvesting for domestic use and irrigation is being promoted, particularly in arid and semi-arid areas [64]. Water harvested from roofs is usually of a better quality than that harvested from land surfaces. One major challenge is getting a sufficient roof area, especially in rural areas, where houses are small or the roofs are made of thatch. Miti Mingi is located within the Nakuru urban area and houses are likely to have bigger and better-quality roof areas for rainwater harvesting compared to East Pokot. In both areas, it is difficult to find households with roof areas exceeding 100 m^2. Therefore, the biggest challenge to exploiting the potential of harvested rainwater for home gardening is the limited roof area. Harvesting runoff from land surfaces and storing it in ponds lined with UV-stabilized waterproof liners would overcome this challenge. However, uncovered ponds lose significant amounts of water from evaporation in drier areas. The water would be suitable for irrigation, but it would have to be purified to make it suitable for domestic use. However, ponds have the added problem of being a mosquito breeding ground, so enclosed tanks could reduce this. Tanks could also be located closer to the house where small-scale gardening takes place, and so encourage use. Shade nets would be more suitable and cheaper for reducing water loss by evaporation and controlling insect pests compared to greenhouses. If greenhouses are used, one can also harvest rainwater from its roof and store it in the pond.

4.2. Household Agriculture, Rainwater Storage Systems, and the Sustainable Development Goals

The integrated practice of HA and RSS can contribute to many of today's global issues. The Sustainable Development Goals (SDGs) provide a useful framework for demonstrating that contribution. Understanding the underlying nexus that needs to be addressed is important to realizing that potential. HA and RSS can contribute to at least eight of the 17 SDGs; on an individual level, particularly goals 2 to 6, and on a more community and global level, goals 11, 12, and 15. The fact that it can contribute to food security, improved nutrition, sustainable agricultural, and sustainable water management practices (goals 2 and 6) needs little explanation. In terms of goal 3, good health and well-being, many researchers have also reported a variety of other benefits to practicing HA, including reductions in depression, anxiety, and body mass index, and increases in life satisfaction, quality of life, and sense of community, [1,26,27]. It is understood to enhance well-being [65], improve physical and mental health [66], and reduce diabetes by providing a diet less based on often imported and highly processed food. In the republic of Nauru in the Pacific, this is exactly what has happened as populations have shifted towards purchasing cheap imported food and away from producing their own, resulting in high levels of obesity and diabetes [67]. HA in itself also provides a medium for physical activity [68] and is often prescribed for therapeutic and mental health benefits, as well as for its use in the treatment of obesity [69]. Whilst providing nutrition, it can also help in educating children about nutrition [70,71], and it is increasingly forming part of the educational curriculum [72]. The estate of New South Wales in Australia, for example, has just this year released a new syllabus for teaching Agriculture at primary school level k-10 [61]. The Food and Agricultural Organization (FAO) has a number of publications to specifically assist with this; for example, a toolkit for setting up and running a school garden [73] and program lessons for "Integrating agriculture and nutrition education for improved young child nutrition [63]. In this way, UA is integral to goal 4, quality education: *Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all*. For a number of reasons, this addresses goal 5, gender equality: *Achieve gender equality and Empower all women and girls*. Firstly, because it is women who predominantly engage in HA and household water management [74], they are the primary benefactors. If collecting water from a distant RSS can save time when collecting water, this can produce more time for other things, such as education. If HA produce is also sold, this will also mean that the women are contributing to the household income, while the children start their education at home through their participation.

Sustainable cities and communities, which *make cities and human settlements inclusive, safe, resilient and sustainable* (goal 11), can be addressed by a change in lifestyle and healthier living, and HA in the urban environment also means greener cities. Cuba, a world leader in UA [67], due to trade embargoes, developed a system called organoponics that relies on neither diesel nor chemical fertilizer. The food is grown close to where it is consumed and organic material is used to fertilize garden beds. The potential reduction in "food miles" and change in consumer consumption patterns addresses goal

12, responsible consumption and production: *Ensure sustainable consumption and production pattern.* Finally, it contributes to goal 15, life on land: *Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.* HA can increase the biodiversity of plants and insects [75]. Organisations such as "Garden Organics" in the UK have set up a "heritage seed" library, which encourages individuals to grow forgotten plant varieties in the face of a homogenizing market. For example, in the US, 90% of the 7000 varieties of apples that used to exist have all but disappeared [76]. Vegetables cultivated all over the old city in Andernach, Germany, are known to maintain "forgotten varieties" [25]. Therefore, extensive home gardening can help maintain genetic diversity and the wealth of the world's collective seed bank, whilst commercial large-scale agriculture tends to focus on a narrow selection of high-yield varieties [77].

While we have only discussed the positives here, there are some negatives and challenges. One particularly malignant issue that warrants serious consideration is the potentially increased risk of malaria due to mosquito breeding grounds associated with urban agriculture [67,78] and RSSsystems [79]. This will need to be mitigated by RSS design [80] and open containers are not generally recommended [81]. Another is diarrhea associated with using wastewater to irrigate and human waste as fertilizer [67]. Jongman and Korsten [79] investigated water quality in rural villages in South Africa in 80 rainwater tanks and concluded that the use of untreated rainwater in crop irrigation or domestic use poses a potential health risk, especially in areas with a high population of immunocompromised individuals, so they advocate treatment before use. A little consideration will also show that to fully realize the potential, there are a number of barriers. For example, the crop yield is highly variable and dependent not only on resources, but on the gardener's skill.

4.3. International Relevance

This paper confirms the relevance of RSS use in HA for semi-arid and semi-humid zones. The findings in this paper may also be relevant to other climate zones, such as tropical areas that have long dry seasons. For example, Bangladesh has fertile land and a small household garden can produce quality vegetables and fruit. However, during winter months, there is little rain and evapotranspiration exceeds rainfall [82], so the water harvested via RSS in the late monsoon can boost HA during the dry. The arsenic-contaminated groundwater and high-level salinity have affected rural tube-well-based drinking water systems and food chains. The high rainfall suggests that RSS could both supply drinking water to the households and also be used for HA. This can be a game changer at household levels in Bangladesh, increasing nutrition and reducing arsenic intake ingested in food or consumed in drinking water [83]. This will contribute to the health and nutrition of children and women and other members of the public in rural areas. It is expected that similar benefits could be realized in many countries internationally.

5. Conclusions and Further Research

Household gardening using rainwater storage systems (RSS) shows great potential for increasing household nutrition and possibly income. In semi-humid and semi-arid regions, such as Nakuru and East Poket in Kenya, where hunger and malnutrition are frequent, it can have a big impact.

If evaporation were controlled, the current 1 ML RSS at the orphanage that includes 8 kL of recycled water per day, as well as a rainfall input from 1400 mm, could potentially support up to 4000 m^2 with a 72% reliability and yield 19,190 kg of vegetables/fruit per year, which is more than enough to meet the WHO requirement of 400 g/p/day for 100 adults (14,600 kg/year) or the 45 adults and 120 children that the orphanage currently supports. Excess or sections of the garden could be sold for profit and other vegetables and supplies bought to maintain food variety and nutrition. Yields in the greenhouse for the same area were found to be less due to the lack of input from the rain into the soil, at 16,860 kg/year. Greenhouses that are large may not be economically viable and shade cloth may be preferable in the Kenyan environment. However, for specialist or off-season cash crops, a greenhouse may still be viable, and this would require a specific analysis.

Analysis has shown that a closed 225 kL RSS has the potential to considerably increase yields for areas up to at least 1000 m^2 if there is ample roof catchment available in the region of 500 to 2000 m^2. Larger roofs may increase the reliability even more. Yields for 1000 m^2 of land in the semi-arid region of East Pokot could be increased by 1849 kg from 1270 kg to 3119 kg by a 225 kL RSS connected to a roof of 1000 m^2. This could supply 85 people with 25% of the WHO recommended daily fruit/vegetable needs. In the semi-humid region for the same system, yields could be increased by 2348 kg from 1854 kg to 4202 kg and supply 115 people with 25% of the daily vegetable needs.

This analysis has shown that there is water available to increase yields. Future research needs to focus on feasibility. It is expected that realistic solutions will necessarily involve a multidisciplinary approach. To realize the higher crop yields, a community education program will be necessary, and it seems most reasonable that this should begin at the youngest age. Cost is always a hindrance to such projects, so designs appropriate for the countries' circumstances should be investigated in more depth. A trial of 225 kL tanks with roof areas would be a good way forward to assess the underlying issues.

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