Article

Improving Household Agriculture with Roof-Harvested Rainwater: A Case Study in Sydney and Nairobi

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Abstract: The production and distribution of a sufficient quantity of food and water of satisfactory quality is at the heart of sustainable development. At the small domestic scale, roof-harvested rainwater can make a significant contribution to food supply and distribution systems (production, handling, storage, and transportation). In this paper, we compare the potential crop production of a small garden plot using three methods of watering: (1) rainfed only with no irrigation; (2) irrigated with the ideal amount of water; and (3) rainwater tanks of various sizes installed and used to irrigate the plot. Yield was determined on the basis of the yield calculation method presented in FAO 33. It was found that yields can be increased considerably by installing a correctly managed rainwater storage system (RSS). A 3 kL RSS connected to a 120 m² roof can increase yields in Nairobi from 40 kg to 96 kg. In Sydney, a larger roof of 200 m² can increase yields from 66 kg to 143 kg. This study makes an important contribution to water and food security-related sustainable development goals.

Keywords: household agriculture; urban agriculture; rainwater harvesting; rainwater storage systems; sustainable housing; nutrition; SDG

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1. Introduction

Freshwater scarcity is one of the prime challenges that the world is currently facing [1]. The increased stress on water supply systems due to rapid population growth, accelerated urbanization, and climate change—along with improved socio-economic development—has increased the demand for both potable and non-potable water [2]. The conflict between limited freshwater resources and increasing water demands have resulted in water shortages in many regions [3]. In addition, changes in rainfall patterns and increased drought days due to climate change have affected numerous countries including Australia, where freshwater scarcity has become a subject of concern [4,5]. Scientists and professionals around the world have been searching for alternative options to satisfy the increasing demand for water in a sustainable way. In this regard, the effective and well-planned harnessing of rainwater can ease the burden on water supply systems and eventually support smarter water use [6].

RWH is not a new idea: it existed even before the advent of large-scale public water supply systems [6,7]. Over recent decades, RWH has received renewed attention as a potential sustainable water management option [8]. It is one of the most feasible ways to replenish both ground and surface water to meet increasing water demands at smaller scales [6]. RWH systems have been adopted widely in many countries such as Australia, the USA, China, India, Iran, and Brazil, primarily to reduce mains water use [6]. In the agriculture sector, harvested rainwater can also be used to cope with droughts and increase

crop yields [8–10]. Evidence suggests that roof-harvested rainwater meets the water quality criteria for general agricultural purposes [11].

Household agriculture (HA) can build resilience for food security and nutrition at the household level while contributing to building closer communities by connecting people with the food production system [12,13]. HA also encourages people to make positive dietary changes that lead to better physical and mental health [11,14]. Moreover, HA supports the environment in several ways, such as temperature reduction, infiltration of runoff, and restoration of biodiversity [15,16]. Overall, HA entwines notions of food and nutrition security with sustainable environment, as well as ideas of beautification, leisure, exercise, and community interaction [14]. This is particularly beneficial for women, children, and older generations, who typically spend more time at home.

In Australian cities, HA is increasing in popularity and is often referred to as urban agriculture, which also includes urban farms [12] and roadside gardens [13]. This practice is encouraged by many local councils in Australia [17]. It may also play an important role in the economy by initiating small businesses based on HA. This trend seems to be growing throughout the developed world, partly due to increased food prices and a search for higher quality foods, particularly organic foods [18,19].

Developing countries also demonstrate an increasing interest in HA out of necessity or due to cultural reasons. For example, in Cuba, organoponics—raised garden beds in urban centres—receive government support and produce a considerable quantity of food near to the point of consumption [19]. In Lesotho, South Africa, thousands of keyhole gardens have been built over the last decade, which has resulted in notable economic and environmental benefits [20,21]. Water is often a limiting resource in HA and is typically sourced from mains [22]. This puts additional pressure on mains water, particularly during droughts or water restrictions [23,24]. Therefore, as recommended by the FAO, the use of an alternative water source, such as harvested rainwater, for HA and urban agriculture may represent a viable option [23,25,26].

In this study, we examined the potential of a RWH system in urban areas of Nairobi (Kenya) and Sydney (Australia), based on several plot sizes and with three different watering methods: (1) rainfed crops without any additional irrigation; (2) irrigated with the ideal quantity of water; and (3) rainwater tanks of various sizes used to irrigate the crops. The intricate relationship between supply and demand was deemed to be a key issue in determining RWH system reliability. The water requirement of crops is primarily a function of evapotranspiration (ET_o). RWH systems were modelled using a daily time-step. Daily climate data were acquired for each location, the ET_o was calculated based on Food and Agriculture Organisation (FAO) 56 [26], and crop production was estimated using FAO 33 [27]. It is expected that this study will serve as an important reference for policy makers, environmentalists, town planners, and non-governmental organisations (NGOs), and will contribute to achieving the United Nations sustainable development goals (SDGs) related to water and food security.

2. Materials and Methods

We selected Parramatta in Sydney (Australia) and Wilson in Nairobi (Kenya) as the study locations. The mean annual rainfall values for Parramatta and Wilson are 960 mm and 891 mm, respectively (with variation of about 10% between the two cities). For both Parramatta and Wilson, the wet season lasts for seven months (November to May) and the dry season for five (June to October). The winter season in both Parramatta and Wilson lasts for three months (June to August). The mean maximum and minimum temperatures of Parramatta are 23 °C and 12 °C, respectively, and 24 °C and 15 °C for Wilson. The evapotranspiration values in Parramatta and Wilson are 1351 and 1703 mm, respectively (26% variation between the two cities). These data show that Wilson is drier than Parramatta and, hence, the crop water requirement for Wilson will be higher than that of Parramatta. The common HA/urban agriculture crops for both Parramatta and Wilson are quite similar, e.g., radish, lettuce, parsley, and spinach (grown all year round); broccoli,

Asian vegetables, and tomatoes (grown all year except in winter); and cauliflower, cabbage, and peas (grown in winter).

In this study, two different roof sizes, 120 m² and 200 m², were considered. The former is typical of Kenyan single occupancy houses, while the latter is typical of houses in Parramatta [28]. Garden areas ranged from 1–50 m² and rainwater storage systems (RSS) of 1–10 m³ were considered to reflect the sizes commonly installed in Australia to meet Building and Sustainability index (BASIX) requirements [29]. The maximum crop yield per m² was taken as the average value of 7.3 kg/m²/year, as reported by Rabin et al. [30] for home food gardens. It should be noted that this study found a huge variety in the yields of home gardens, ranging from 0.44 to 22 kg/m², which is in line with the range of 0.22 to 20.17 kg/m² as reported by Foeken et al. [31] for Nakuru, Kenya. Both of the selected locations have a piped water supply. It was assumed that all indoor water requirements would be met by the piped water system, while irrigation water would be provided by the RSS.

The daily agro-climatology data used to calculate the daily ETo of the HA area (Table 1) and to perform the RSS water balance included the following:

- Rainfall in mm/day;
- Maximum and minimum temperature in °C;
- Dew point temperature in °C, used to calculate relative humidity;
- Solar radiation in MJ/m²/day; and
- Wind velocity in m/s.

Table 1. Summary of selected climate data.

Location	Period of Data	Average Annual Rainfall (mm)	ETo
Parramatta (Sydney)	1965–2020	960	1351
Wilson (Nairobi)	1959–1988	891	1703

These data were obtained from nearby weather stations according to the method presented in FAO 56. The ETo of Prospect Reservoir, some 15 km away from the selected site in Sydney, was used. In Kenya, where there was a lack of access to recorded data, satellite was used to supplement the recorded daily rainfall data. Satellite data were obtained from the NASA Langley Research Centre POWER Project [32]. Satellite data are increasingly used for this type of study [33–36]. Maximum and minimum humidity values were calculated from minimum and maximum temperature and the dew point temperature data, following the method presented by Eccel in [37]. Results for ETo were compared with CLIMWAT [38] and the World Meteorological Organization (WMO) [39] averages for validation purposes.

To assess the reliability of the RSS, a daily RSS balance model was used based on the yield after spillage model described by Fewkes and Butler [40]. In the adopted model, the rainfall was regarded as inflow and the release and possible spillage as outflow [41]. It was assumed that RSS is not connected with mains water and, hence, the RSS was not always full. The release from the RSS was estimated by the following equations:

$$R_t = D_t \text{ if } I_t + S_{t-1} \geq D_t \quad (1)$$

$$R_t = I_t + S_{t-1} \text{ if } I_t + S_{t-1} < D_t \quad (2)$$

where D_t is the daily water demand (m³) on day t , S_{t-1} is the RSS storage at the end of the previous day (m³), R_t is release from RSS (m³), and I_t is inflow (m³). Spillage from RSS (SP_t) (m³) was calculated by the following equations:

$$SP_t = I_t + S_{t-1} - D_t - S_{MAX} \text{ if } I_t + S_{t-1} - D_t > S_{MAX} \quad (3)$$

$$SP_t = 0 \text{ if } I_t + S_{t-1} - D_t \leq S_{MAX} \quad (4)$$

where S_{MAX} is the design storage capacity (m^3) of RSS. The RSS storage S_t at the end of day t was computed by:

$$S_t = S_{MAX} \text{ if } SP_t > 0 \quad (5)$$

$$S_t = S_{t-1} + I_t - R_t \text{ if } SP_t = 0 \quad (6)$$

The daily irrigation water demand is a function of the ETo from the HA plot and was also determined on a daily basis using the method outlined in FAO 56 [36] with an assumed crop coefficient value (Kcb) of 1. The reliability of the RSS is defined by:

$$\text{Reliability} = \frac{ETa}{ETx} \quad (7)$$

where ETx is the maximum possible evapotranspiration over the plants' lives with unlimited water supply and ETa is the actual total evapotranspiration over the life of the crop. In practice, ETx is generally greater than ETa as most plants face some level of water restriction in life.

The yield at the end of the growing season (Y_a) was calculated using the FAO 33 [37] method, as presented in Equation (8). It is a function of ETx and ETa , the yield response factor (K_y), and the maximum crop yield (Y_x).

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y \left(1 - \frac{ETa}{ETx}\right) \left(1 - \frac{Y_a}{Y_x}\right) = K_y \left(1 - \frac{ETa}{ETx}\right) \quad (8)$$

where Y_a is a function of the maximum crop yield, Y_x (here taken as $7.3 \text{ kg}/m^2/y$), ETx and ETa , and the yield response factor (K_y).

3. Result and Discussion

The average annual reliability of RSSs, with sizes from $1\text{--}10 \text{ m}^3$, as compared with rainfed only (None) and unlimited water supply (Mains), is presented in Figure 1.

Figure 1. Average annual RSS reliability for various HA areas (1, 2, ..., 10 indicate size of RSS in m^3).

As can be seen in Figure 1, for the smaller HA (or garden) areas, 100% reliability can be achieved. As expected, reliability decreases with increasing garden size; however, for

the larger RSSs, all water needs can be met even for larger areas. In Sydney, the 10 m³ RSS with a 120 m² roof can provide 94% reliability for a 50 m² HA, or, with a 200 m² roof, reliability increases to 97%. In Nairobi, the corresponding reliabilities are 72% and 78%, respectively. However, with a 120 m² roof, Nairobi can still support 20 m² of HA 95% and 97% of the time with a 200 m² roof. Figure 2 presents the corresponding yields.

Figure 2. Average annual crop yield (kg) (1, 2, ..., 10 indicate size of RSS in m³).

Rainfed reliability was calculated to be 50% for Sydney and only 35% in Nairobi, potentially due to the rainfall distribution rather than the annual rainfall, which is similar for both cities. The yields for a 20 m² HA area under the rainfed scenario were 67 kg/y in Sydney, and 44 kg/y in Nairobi, as shown in Figure 2.

For the 120 m² roof and 20 m² HA area, the 10 m³ RSS increased maximum yields to 146 kg in Sydney and 129 kg in Nairobi. This represents an increase of 79 kg and 85 kg above the rainfed values for Sydney and Nairobi, respectively, demonstrating that Nairobi benefits more than Sydney does from the installation of an RSS system. A 3 m³ RSS connected to the same roof still increased yields from 67 kg to 142 kg in Sydney, approaching the maximum yield for this city, and from 44 kg to 103 kg in Nairobi. Even a small 1 kL RSS can considerably improve yields, nearly doubling them from 67 kg to 125 kg in Sydney and from 44 kg to 84 kg in Nairobi. In fact, for the 20 m² HA area, the majority of the increase in yield was realised by a 3 kL RSS in Sydney and a 5 kL RSS in Nairobi (Table 2).

Table 2. Average yield (kg/year) for various RSS sizes (m³) for 20 m² household agricultural (HA) area.

Location	Roof	Rainfed	1	3	5	7	10	Full
Sydney	120	67	125	141	145	146	146	146
Sydney	200	67	129	143	146	146	146	146
Nairobi	120	44	84	103	114	122	129	146
Nairobi	200	44	88	111	121	129	135	146

The WHO recommendation for healthy nutrition is 400 g/p/day of fruit and vegetables, which equates to 146 kg/p/year. Even with just the average yield assumed in this study, an HA area of 20 m² can nearly meet this requirement for one person. It has been suggested that each person requires 18.5 m² of land to provide their fruit and vegetable needs [42], which is in agreement with the findings presented here.

Yield continues to increase with HA area, simply because all areas are capable of yielding crops even under rainfed conditions. However, in the urban environment, more space is not always available. For various reasons, it may be advantageous to increase the yield of a smaller plot, rather than increasing the area of the plot. It should be noted that Foeken et al. [31] found that, in Nakuru, Kenya, there was an inverse relationship between plot size and yield, with smaller plots yielding more per m². This, they assume, is because the smaller plots were located closer to living quarters and so were better attended to. This may also mean that they were better watered. They reported a maximum yield of 20.17 kg/m², which they related to plots smaller than 10 m². For plot areas from 10 to 99 m², an average yield of only 4.73 m² was recorded. If the average yield, approaching 20 kg/m²/year, could be achieved for a 20 m² HA area, then the total yield would be 400 kg/year, or enough for 2.7 people according to the WHO's recommendations. This is a significant contribution to the food supply of a small household.

The average amount of vegetables that can be produced from a 20 m² plot was determined to be 7.3 kg/m²/year, based on a study of 2608 mixed stand communities or home food gardens [30] and assuming three crops per year, as shown in Table 3.

Table 3. Average yield (kg/year) comparisons for various plot sizes.

Location	Plot Size (m ²)	Max. Crop Yield (kg/m ² /Year)
Sydney ^a	20	7.3
Nairobi ^a	20	7.3
Nakuru ^b	20	7.21
Nakuru ^b	10–99	4.73
Nakuru ^b	100	6.50
East Poket ^b	20	7.21
East Poket ^b	40–60	5.21
East Poket ^b	100	4.85
New Jersey, USA ^c	Mixed (mode)	7.2
New Jersey, USA ^c	Mixed (upper)	6.35

^a = This study, ^b = Amos et al. [11], ^c = Rabin et al. [30].

It should be noted that the analysis in this paper assumes that irrigation takes place at an appropriate time such that there is no water loss through deep percolation, or runoff. Poor irrigation practices wastewater and may reduce the efficiency, reliabilities, and yields reported here. On the other hand, careful management may assist in increasing reliability and efficiency beyond what is reported here. Careful selection of crops with low water requirements and timing of planting, as well as deficit irrigation practices, may also increase reliability and efficiency. Other management techniques such as using shade cloths may reduce evapotranspiration loss. Yield can also be affected by soil quality, pest management, and plant varieties. Plant varieties and diversity also affect the nutritional value of the foods grown. All of these factors point towards a need for the education of home gardeners to achieve widespread successful use of RSS in HA, and to thereby build resilience in food and water supply security. It should be noted that greywater from households can easily be integrated into RSSs and, in such cases, the reliability of the RSS would increase further.

4. Conclusions

This study examines the potential crop production of small garden plots using harvested rainwater. It was found that crop yields can be increased considerably in urban household agriculture (HA) by installing an appropriate rainwater storage system (RSS). Yields could potentially be increased further through educated gardening practices. It

should be noted that increasing agricultural education is an essential component of improving home crop yields, along with increasing the available water supply. There is a need for the widespread education of home gardeners. Moreover, house designs should incorporate HA as part of the design process, with 20 m² of HA areas proposed as an appropriate target. This study makes an important contribution to the sustainable development of water and food security for small households.

This study presents a simplistic method of modelling irrigation use; therefore, a more in-depth study focusing on all irrigation uses would be useful. Particular attention should be paid to water requirements, evapotranspiration, and yield. Relationships between total available water, monthly and seasonal variation in rainfall, rainfall categories in the various regions of Australia and Africa, and their influence on reliability and efficiency of RWH systems should also be explored to advance understanding of RWH's potential in urban agriculture and the contribution it can make to greener cities and attaining sustainable development goals.

Sustainable development, sustainable water management, and food security are integrally related and must be considered together when allocating food and freshwater resources to competing purposes and users. However, in arid and semi-arid regions, water system sustainability and food security often face challenges related to infrastructure, physical resources, and socio-economic conditions. To overcome the challenges present in attaining sustainability in water management and food security, the present study highlights several areas deserving of further research.

The findings of this simulation study should be verified using field observations before being applied in practice. Such a field verification would allow for refinement of the simulation model and the associated findings. It should also be noted that the findings of this study are location specific, and that other locations will have different climatic characteristics and thus will generate different results. Furthermore, the cost of RSSs may need to be subsidised by governments or non-governmental organisations in Africa and other developing countries, as most households in these countries may not be able to afford a large RSS.

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