Optimization of rainwater harvesting system design
for smallholder irrigation farmers in Kenya: a review

Kevin O. Odhiambo, Basil T. Iro Ong'or and Edwin K. Kanda

ABSTRACT

The adverse effects of climate change on agriculture have been felt across the globe. Smallholder farmers in sub-Sahara Africa are particularly more vulnerable to the effects of climate change leading to loss of income and livelihood thus affecting global food security. Rainwater harvesting (RWH) is emerging as a viable option to mitigate the negative effects of climate change by supporting rain-fed agriculture through supplemental irrigation. However, smallholder farmers are still grappling with a myriad of challenges hindering them from reaping the benefits of their investment in RWH systems. This review explores some of the factors behind the poor performance of RWH systems in Kenya and also seeks to suggest techniques that can be applied to optimize the design parameters for improved performance and the adoption of RWH systems. According to the review, RWH has the potential to mitigate the adverse effects of climate change among smallholder farmers. It allows for crop production beyond the growing season through supplemental irrigation. However, their impacts have been minimal due to the consistent poor performance of RWH systems. This is attributed to inefficiencies in design and construction brought about by lack of required technical skills among RWH system designers and implementers. Proper design and implementation are therefore paramount for better performance and adoption of RWH systems in the region. This will ensure that RWH systems are reliable, technically and economically feasible as well as possess a desirable water-saving efficiency.

Key words | crop water requirements, irrigation, optimal design, rainwater harvesting system, smallholder farmers

Kevin O. Odhiambo (corresponding author)
Basil T. Iro Ong'or
Edwin K. Kanda
Department of Civil and Structural Engineering,
Masinde Muliro University of Science and
    Technology,
P.O. Box 190, 50100 Kakamega,
Kenya
E-mail: odhiamboowino2016@gmail.com

HIGHLIGHTS

- Improved design of rainwater harvesting system (RWH).
- Increased adoption of RWH systems.
- Improved resilience to climate change among smallholder farmers.
- Enhanced food security and access to clean water.
- Improved performance of RWH systems.

INTRODUCTION

Climate change has significantly affected the livelihood and income of farmers across the globe (IPCC 2014). In sub-Sahara Africa (SSA), climate variability and change are considered a great threat to agriculture. Small-scale farmers who are vital in ensuring food security in the region are particularly more vulnerable to the adverse effects of climate change such as drought and flood (Verchot *et al.* 2007). During drought for instance, water sources for irrigation dry up leading to crop failure and subsequent famine resulting in social, economic and environmental losses (Mulwa *et al.* 2016). Under some extreme circumstances, the governments are prompted to provide food aid to cushion the population against malnutrition (Mburu *et al.* 2015). Climate change effects have further caused strain to the limiting water resources in SSA hindering the ability to expand irrigation (Vincenza *et al.* 2016).

To develop resilience, farmers have adopted different techniques such as rainwater harvesting (RWH), irrigation and planting of drought-resistant crops (Mburu *et al.* 2015). RWH in this context can be described as 'a method of inducing, collecting, storing & conserving local surface runoff for agriculture production' (Ibraimo 2007). RWH has the potential of increasing rain-fed agriculture production as well as reducing effects of soil erosion. It also allows crop production beyond the growing season through supplemental irrigation (Li *et al.* 2000). RWH can also be an effective source of water for domestic water supply in areas with a limited water supply such as arid and semi-arid areas. It can be easily collected and used without significant treatment (Nolan & Lartigue 2017). A study by Qin *et al.* (2019) proved that rainwater buffer tank significantly reduced the runoff peak flow hence had the capacity to protect against the adverse effects of flood such as damage to properties and loss of life.

Appropriate RWH techniques coupled with an efficient Decision Support System have become indispensable tools for conducting sustainable agriculture in the face of climate change (Fenu & Malloci 2020). The significance of RWH in this context is to make use of the available rainwater that is experienced in Kenya to increase crop production and enhance resilience to climate change. Research has shown that RWH can be effective in increasing crop production and improving adaptability to climate shock. For instance, a study by Kahinda *et al.* (2007) showed that supplemental irrigation of maize in Zimbabwe using rainwater increased yields and reduced the risk of crop failure. The collection and use of rainwater is therefore seen as a suitable remedy for adverse effects of drought among small-scale farmers.

Despite these known benefits, the adoption of RWH systems by small-scale farmers in Kenya for irrigation is relatively slow (Annastacia 2018). A study by Matiti (2018) showed that many RWH systems in Kenya are not performing as expected. The study indicated that a number of RWH systems are not reliable and are technically inefficient. Furthermore, a report by Chamwada (2019) indicated that a number of farm ponds and reservoirs constructed under the government household irrigation and water storage program do not fill to their capacity even after prolonged rainy seasons.

Wachira (2013) also noted that many smallholder farm ponds suffer high water losses through seepage and evaporation such that the ponds dry up before the end of the growing season. A study by Matiti (2018) found out that a good number of reservoirs have reduced capacity as a result of heavy siltation while some are completely damaged by water that overtops their banks leading to collapse. Consequently, the impact of the systems has been minimal with farmers taking relatively a long time to return their investment, while other investments on the same are completely lost as a result of the system failure (Kiggundu *et al.* 2018).

This review aimed at exploring the factors behind the poor performance of the many RWH systems in Kenya while attempting to render solutions for better design and implementation of the system in the region. It provides guidelines for the effective design and construction of an optimal RWH system for smallholder irrigation farmers. This will help designers and implementers of RWH systems to understand various approaches that can be applied to optimize the design parameters of the systems in order to

contribute to better performance and improved adoption by smallholder farmers in the region hence enable them to develop resilience to climate shock.

The review is structured as follows: First, a brief description of RWH techniques used by smallholder irrigation farmers in the region is provided. Secondly, factors affecting the performance of RWH systems used by smallholder farmers have been explored. Finally, the review looked into the design aspects for an optimal RWH system for the region; consideration was made on ways of optimizing the design parameters to improve the RWH systems reliability, technical feasibility as well as the water-saving efficiency in the area. At the end, conclusions and recommendations are provided.

RWH SYSTEMS TECHNIQUES AND INTERVENTIONS FOR SMALLHOLDER IRRIGATION IN KENYA

There are basically two methods of harvesting rainwater commonly used by smallholder farmers in Kenya, namely *in situ* and *ex situ* RWH. *In situ* RWH techniques involve capturing and using the rainwater at the farm through employing methods that increase the amount of water stored in the soil. Commonly applied methods include contour bunds, use of pits and strip catchment. Other methods of conservation agriculture such as deep tillage and contour farming are also classified under this technique (Hatibu & Mahoo 1999).

Ex situ RWH involves capturing rainwater outside the farm. The techniques involve the collection and storage of rainwater in natural or man-made reservoirs such as ponds, wells, small earth dams and other cisterns of different sizes for supplemental irrigation (Moges *et al.* 2011). They may be accompanied by intermediate storage for later use in supplemental irrigation (Black *et al.* 2012). This review will focus on *ex situ* RWH techniques, especially the construction and performance of farm ponds and reservoirs for small-scale irrigation.

A number of *ex situ* RWH systems have been used for smallholder irrigation in Kenya. Most commonly applied methods include water pans, rock catchments, earth dams and water ponds (Aroka 2010). Smallholder farmers across Kenya have dug water pans and ponds to capture and store runoff for irrigation. The pans and ponds are basically

small earth dams of shallow depths ranging between 1 and 3 m with a dug stream and an embankment (Kimani *et al.* 2015). Several interventions have been carried out by the Kenyan government as well as other development agencies to promote RWH pans and ponds across the country (Chamwada 2019). Notable programs include a household irrigation and water storage program that is implemented by the National Irrigation Authority, Billion dollar alliance project; a partnership project between the Kenyan government, World Bank and World Agroforestry (ICRAF) for RWH in various regions of the country (Onyango 2017).

The National Irrigation Authority through the household irrigation and water storage program has implemented over 2,363 water pans in 12 counties since its inception (NIB 2019). Individual farmers have also been active in promoting RWH techniques in Kenya; this is evidenced by a number of farmers taking up the construction of ponds for irrigation across the country as well as the rise in manufacturing and importation of the geomembrane for pond lining in the country (Chamwada 2019).

Rock catchments that involve directing runoff from rock catchment surface to a reservoir usually consisting of a masonry wall have also been used in some semi-arid parts of Kenya. In some areas of Kitui and Makueni counties of Kenya, rock catchment and storage have been implemented to boost crop production through irrigation as well as to provide water for domestic use (Kimani *et al.* 2015). The stored water can be conveyed by gravity or pumping for irrigation to adjacent farmlands (Matiti 2018).

Smallholder farmers have also used hand-dug wells to store rainwater for supplemental irrigation. The wells have been constructed mainly in areas, where the water table is relatively high and at the river beds of seasonal rivers (Matiti 2018). They have been effective in storing rainwater during wet seasons for supplemental irrigation in dry periods. Water from the well can be manually lifted or pumped to a raised reservoir for subsequent application to irrigation fields (Aroka 2010).

Factors affecting RWH system performance in Kenya

Ex situ RWH techniques have been in existence in Kenya for many decades. Farmers and households have used the

Table 1 | Factors affecting RWH system performance in Kenya

S/N	Category	Source
	Technical challenges	
1.	Inadequate design (inappropriate catchments, design rainfall and storage)	Munyao (2014), Matiti (2018) and Annastacia (2018)
2.	Seepage and evaporation losses	Wachira (2013) and Kimani *et al.* (2015)
3.	Siltation	Thome (2005) and Karara (2018)
4.	Lack of effective operations and maintenance program	Wanyonyi (1998) and Ngigi *et al.* (2005)
	Socioeconomic factors	
5.	Ineffective management of RWH systems	Ngigi *et al.* (2005) and Black *et al.* (2012)
6.	Inefficient water utilization	Njuguna (2014)

techniques to supplement rain-fed agriculture as well as augment the available water resources (Black *et al.* 2012). In the last three decades, there has been increasing interest toward the promotion of *ex situ* RWH systems in Kenya. The national governments, NGOs and other development agencies have initiated a number of projects to harness and store rainwater for irrigation in Kenya. However, many of the RWH systems constructed are not performing as expected (Matiti 2018). As a result, their adoption by smallholder farmers in Kenya is relatively slow. This can be attributed largely to technical and socioeconomic factors. Table 1 summarizes the key factors affecting RWH systems adoption by smallholder farmers in Kenya.

Technical inefficiencies in design and construction have been noted to contribute significantly to the inability of RWH systems to meet the expected water demand (Annastacia 2018). In addition, many RWH system implementers including individual farmers and organizations, lack access to adequate construction guidelines to enable them to make proper decisions with regard to the implementation of the RWH systems (KRA 2010). A study by Munyao (2014) revealed that a number of smallholder farmers lack technical skills for proper siting and construction of an appropriate RWH system. Consequently, a number of smallholder farmers in Kenya have ended up constructing RWH systems without any regard to proper design procedures making the systems prone to failures.

According to a study by Wanyonyi (1998), inadequate design hinders farmer's ability to maximize the benefits of RWH systems. Poorly designed farm ponds do not fill to their capacity even after prolonged rainfall. Improper siting of farm ponds leads to inadequate catchment resulting in low runoff collection. As result, a number of structures constructed for RWH do not sustain the crop water demands for the area (Matiti 2018). Appropriate RWH system design is therefore necessary to ensure that there is enough storage to meet the expected demand during the period of scarcity (Munyao 2014).

A suitable selection of design rainfall is required to properly size the storage in relation to the catchment area for effective RWH (Mati *et al.* 2005). If the rainfall in the area is less than the design rainfall, the stored water cannot meet the crop water requirement. However, if the design rainfall exceeds the expected amount, the system could be damaged and at times crops may be lost as a result of flood (FAO 2014a, 2014b).

Seepage and evaporation water losses have likewise significantly affected the performance of RWH systems in Kenya (Wachira 2013). The losses may account for 20–30% of the total volume (FAO 2010) and are more aggravated in arid and semi-arid areas that are characterized by loose soils and extreme weather conditions (Kimani *et al.* 2015). According to a study by Gachene & Kimaru (2003), a greater portion of arid and semi-arid lands of Kenya, where RWH is practiced, consist of black cotton soils (vertisols) which have a cracking tendency especially when dry hence cannot hold water during the wet season. A report by Chamwada (2019) further indicated that the majority of farm ponds implemented under the government water harvesting program have failed to supply the expected water demand owing to high seepage and evaporation losses. Table 2 shows seepage losses for various soils.

In addition, RWH systems for irrigation have also been limited in a capacity as a result of heavy siltation. A number of farm ponds and small earth dams constructed across the country have been abandoned due to reduced capacity caused by the deposition of sediments (Thome 2005). A study by Karara (2018) on the Kabiruini dam in Nyeri, Kenya noted that heavy siltation significantly hampered the dam's ability to supply the demand water for irrigation. It indicated that the dam depleted within two

Table 2 | Seepage losses (mm/day) for various soil types

Natural soil type	Seepage losses (mm/day)
Sand	25.00–250
Sandy loam	13.00–76
Loam	8.00–20
Clayey loam	2.50–15
Loamy clay	0.25–5
Clay	1.25–1.0

Source: MoWi (2005).

years of its desiltation due to sedimentation from the overlying catchment hence affecting substantially its productivity. Matiti (2018) further noted other challenges affecting the performance of RWH systems in Kenya including lack of requisite facilities such as animal watering troughs, poor accessibility, lack of proper intake and water draw-off structures, and unavailability of protective fence around many water points. The study proved that many water systems therefore suffered damage and contamination by animals as well as people during access limiting their usefulness.

Lack of efficient management and effective utilization of the limited stored water is also an impediment to the success of many RWH systems in Kenya. The absence of proper management strategy has contributed to the failures of many RWH systems in Kenya (Ngigi *et al.* 2005). Many smallholder farmers lack training in pond management such as essential skills in controlling rapid siltation and protection of pond liners (Munyao 2014). A study by Black *et al.* (2012) noted that a number of the farmers with installed pond liners suffered damage to the liner during the installations and operations compromising the usefulness of the liner.

Finally, lack of economic diversification in the utilization of the impounded rainwater has been identified as a major setback to the success of RWH for irrigation in Kenya (Matiti 2018). Chamwada (2019) also noted that a number of RWH systems have been constructed without regard to farmer's knowledge of irrigation methods as well as crop production. As a result, many farmers have used the stored water carelessly planting crops of low market values using water inefficient methods.

Design and operations aspects of an optimal RWH system for irrigation in Kenya

The main objective of RWH system for irrigation is to ensure the availability of an adequate amount of water for crop production. Effective design of RWH system therefore encompasses the areal precipitation, catchment surface area, water storage as well as the intended water use for the system (Rozaki *et al.* 2017). Studies have shown that rainfall intensities and distribution in a number of catchments in Kenya are adequate to produce sufficient runoff to sustain crop production during the dry season (Karara 2018; Matiti 2018). However, Matiti (2018) highlighted the poor performance of RWH systems making them unable to meet the crop water requirement in many cases.

Designing a suitable RWH system thus calls for the optimization of design parameters including the climatic, geological, hydrological and hydraulics conditions of the specific area under consideration for the maximum benefit (FAO 2014a, 2014b). An optimal RWH system is considered to be reliable, technically feasible and possesses a high water-saving efficiency (Matiti 2018). An appropriate design to achieve optimum standards therefore requires a systematic determination of climatic, hydrological and hydraulic parameters as well as an understanding of ways of optimizing the design parameters for maximum benefits (Mekdaschi Studer & Liniger 2013).

Optimization of RWH system design for reliability

Reliability of RWH system is the probability that the system will supply the required demand of water within a given time (Baek & Coles 2011). It is calculated from the water balance method by taking into account the catchment size, the storage volume, water demand and the evaporation losses as in the following equation (Ndomba & Wambura 2010):

$$0 \leq V_t = (V_{t-1} + Q_t - D_t) < V_S \tag{1}$$

where V_t is the volume of water in the pond at present, V_{t-1} is the volume of water in the pond that remained from the previous rainy season, Q_t is the rainwater collected at present, D_t is the total consumption per month and V_s is the volume of the pond.

The reliability index can be obtained from the water balance model using the following equation (Baek & Coles 2011):

$$R = \frac{\sum (D_t - \mathrm{De}_t)}{\sum D_t} \tag{2}$$

where R is the reliability index of the catchment – RWH system, D_t is the total demand for water for the crop season and De_t is the total deficiency for water.

However, in practice, the reliability index is determined using probability distributions or performance functions using the period when the RWH system does not meet the crop water demand. The following equation (Baek & Coles 2011) is applied:

$$\mathrm{Reliability} = \left(1 - \frac{\sum\limits_0^r \mathrm{Failure\ months}}{\sum\limits_1^n \mathrm{Months}}\right) * 100\% \tag{3}$$

The reliability index has been used as a good indicator for evaluating the performance of RWH systems. A value closer to 1 indicates high system reliability (Matiti 2018).

The reliability of RWHS systems is ensured by the optimization of the design parameters including design rainfall, catchment area to storage volume ratio as well as the water-use techniques (Njuguna 2014). Design rainfall 'the total amount of annual rainfall at which or above which the catchment will provide sufficient water to meet crop needs' is a critical factor in determining the reliability of RWH system (FAO 2014a, 2014b). Appropriate choice of design rainfall is necessary to ensure that the catchment produces enough runoff to meet the crop water demand (Mati *et al.* 2005). The design rainfall is determined through probability analysis of annual rainfall series that occur with desired frequency. It can be determined using the empirical formula in Equation (4) (Dirk 2013);

$$P(\%) = \frac{m - 0.375}{N + 0.25} * 100 \tag{4}$$

where P is the frequency of rainfall in percentage or the probability %, m is the rank order of rainfall series sorted

from the lowest to the highest and N is the number of years of the rainfall series.

For optimal design in tropical humid regions such as Kenya, the use of long-term series of rainfall is recommended with a rainfall magnitude that occurs with 90% frequency. If the rainfall is less than the design rainfall, the stored water cannot meet the crop water requirement. If the design rainfall exceeds the expected amount, the system could be damaged and at times crops may be lost as a result of flood (FAO 2014a, 2014b).

The catchment area in this context refers to the surface area which collects runoff for use in smallholder irrigation. The surface may be a small watershed, rooftops of houses, farm sheds and greenhouses (Aroka 2010). Runoff generation of a catchment depends on the area of the surface as well as the characteristics of the catchment (FAO 2014a, 2014b). The reliability of RWH systems is thus a function of its catchment area and runoff collection efficiency in relation to the intended water use. A simple method of correlating storage volume, runoff depth and catchment area can be given by the following equation (Rozaki *et al.* 2017):

$$S_v = \frac{Q * A}{1,000} \tag{5}$$

where S_v is the storage in m³, Q is runoff depth in mm and A is the catchment area in m².

The runoff depth Q can be calculated from the following relationship equation (Rozaki *et al.* 2017):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{6}$$

where P is the accumulated rainfall in (mm), and S (mm) is the potential maximum moisture retention after the beginning of runoff calculated by the following equation (FAO 1993):

$$S = z\left(\frac{100}{\mathrm{RCN}} - 1\right) \tag{7}$$

where $z = 254$ for metric units, and RCN is the runoff curve number (estimated from tables).

For optimal design and operations, there is need for careful selection of the design rainfall for the catchment. The RWH system design should take into consideration the maximum potential rainfall (P) that is experienced at 90% frequency. The design must also take into account careful consideration of the appropriate runoff curve numbers that should be an accurate representation of the land-cover type and hydrologic condition of the catchment area. The maximum volume of the pond (V) can therefore be determined that can hold the desirable quantity of runoff (Q) from the catchment area and satisfies the crop water requirement (D_t).

Optimization of RWH system design for techno-economic feasibility

RWH systems design can also be optimized for technical feasibility. Under this consideration, the design should try to answer the question 'can it be done with the prevailing resources?' (Senkondo *et al.* 2004). For RWH systems, technical feasibility is largely a factor of the precipitation that is experienced within a given catchment (Matiti 2018). If the rainfall experienced within an area is considered adequate, there exists a potential for harvesting and storage. The adequacy of rainfall for harvesting and storage is determined by establishing the design rainfall of a given catchment area (Mati *et al.* 2005).

To optimize design for maximum benefits of RWH systems, it must be proved to be technically and economically viable (Rozaki *et al.* 2017). Investment analysis can be used to provide useful information for decision-making before constructing RWH systems. Economic analysis of the net present value (NPV), the internal rate of return (IRR) and cost–benefit ratio (B/C) can be used to determine if the RWH system is economically viable (Senkondo *et al.* 2004). NPV aims to determine the current value of the project on forecasted net flows which present the future benefits. NPV can be calculated from the following equation (Badiru & Omitaomu 2007):

$$NPV = \sum_{1}^{n} \left(\frac{C_t}{(1+r)^t} - C_o \right) \tag{8}$$

where t is the time of cash flow, r is the discount rate, n is the depreciation period, C_t is the net cash inflow at time t and C_o is cash outflow.

The RWH system is feasible when the NPV is positive (Stec & Martina 2019).

IRR is the discount rate that makes the NPV of all cash inflows of a project equal to zero. A feasible project is one whose IRR is positive and higher than the decided discount rate. If the IRR calculated is greater than the reference rate, then the adoption of RWH system in the area is economically viable. If the IRR determined is less than the chosen reference rate, then the construction of RWH system in the area is economically unattractive (Rozaki *et al.* 2017).

B/C is also used to analyze the economic viability of RWH system investment. The costs and benefits associated with the project are spread throughout the life cycle of the project. For RWH systems, initial costs involve the costs of constructing the system, while operations and maintenance costs are incurred during the project's active life (Matiti 2018).

Benefits of RWH systems can be estimated both onsite and offsite. Onsite benefits in this context involve the quantity of crops harvested and their associated value, while offsite benefits may be approximated based on the opportunity cost such as flood protection and soil conservation (Senkondo *et al.* 2004). B/C is the ratio of discounted benefits to costs. If the value is more than 1, then the project is acceptable from the financial perspective; while a value less than 1 shows that the project has a negative financial return hence not acceptable (Rozaki *et al.* 2017).

B/C can be approximated based on the following equation (Badiru & Omitaomu 2007):

$$B/C = \frac{\sum_{1}^{n} B_t(1+r)^t}{\sum_{1}^{n} C_t(1+r)^t} \tag{9}$$

where B_t is the benefit at time t, r is the discount rate and C_t is the initial cost at time t.

The design of RWH systems therefore calls for the optimization of design parameters to achieve maximum economic benefits.

Optimization of RWH system design for water-saving efficiency

RWH system design can also be optimized for the maximum water-saving efficiency. The water-saving efficiency refers to

the amount of water that has been conserved against the overall demand of water in the area (Matiti 2018). It depends on the rainfall characteristics of the catchment, catchment size and water demand pattern of the area (FAO 2014a, 2014b). Water-saving efficiency enables one to understand and judge whether a given storage is sufficient to supply the expected demand within a given time. The efficiency can be calculated based on the following equation (Vincenza *et al.* 2016):

$$E = \frac{\sum_{i=1}^{T} R_i}{\sum_{i=1}^{T} D_i} * 100 \tag{10}$$

where E is water-saving efficiency in %, R_i is the total volume of rainwater collected per given period in m³, D_i is the water demand for crop growth in m³ and T is the total time under consideration.

Maximizing on water-saving efficiency of RWH system can be achieved through a number of techniques including optimal siting of the RWH system, appropriate design of the pond capacity, seepage and evaporation losses control as well as effective management of the stored water (Matiti 2018). The RHW system location should allow for the maximum collection and storage from the catchment. The size and dimensions should be designed such that the RWH systems can collect and store a significant amount of water for crop production (Mati *et al.* 2005). An optimal RWH system design allows for the maximum collection and storage to meet the demands of the crops throughout the rainfall distribution period. The storage capacity should be adequate to optimize the planting days after the end of the effective rainfall (FAO 2014a, 2014b).

Storage capacity can also be maximized by minimizing losses through seepage and evaporation (Rozaki *et al.* 2017). To control pond seepage, appropriate lining material can be used depending on costs and availability. Lining using soil base consisting of clay blanket is often preferred in many parts of Kenya because it is cheap and locally available (Fox *et al.* 2005). For small RWH systems, synthetic liners such as geomembrane may be used to prevent water leaks. In some cases with high evaporation, shade covers may be applied (Mati *et al.* 2005).

A number of RWH systems in Kenya have been limited in capacity due to siltation (Karara 2018). For optimal design and operations, RWH systems should have appropriate silt control structures to trap sediments and ensure the maximum utilization of the storage capacity (Matiti 2018). Finally, to maximize the benefits of RWH systems, it is prudent to incorporate an appropriate water use technology. A study by Njuguna (2014) found that optimum benefits of RWH systems for irrigation are achieved by integrating the system with water-efficient technologies such as drip irrigation.

CONCLUSION AND RECOMMENDATIONS

The potential benefits of RWH in Kenya cannot be over-emphasized. It can provide the needed additional water resource to bridge the gap in water scarcity; support rain-fed agriculture through supplemental irrigation as well as reduce the adverse effects of climate change such as drought and flood. The Kenyan government and other development partners have been active in promoting these RWH technologies in the recent past. Furthermore, individual smallholder farmers have also shown a keen interest in adopting the RWH system techniques as a solution to irrigation water challenges in the last decade. This has seen a rise in the construction of water pans, small earth dams, rock catchments, shallow wells and ponds in different parts of the country.

However, these interventions have achieved little impact owing to consistent poor performance in many areas. From this review, a number of factors were noted to contribute to this low performance and include inadequate design of RWH systems, seepage and evaporation losses, siltation, lack of effective operation and maintenance program, ineffective management as well as inefficient utilization of the stored water. Proper design and implementation are therefore essential for better performance and adoption of RWH systems in the region. This will ensure that RWH systems are reliable, technically and economically feasible as well as possess a desirable water-saving efficiency.

Research on ways of improving the RWH system performance to maximize benefits is thus necessary. RWH system designers should therefore explore techniques of optimizing the design parameters including geological,

hydrological and hydraulic parameters for each catchment under consideration to achieve the desirable RWH systems reliability, technical feasibility and water-saving efficiency.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Annastacia, N. K. 2018 *Rainwater Harvesting as an Adaptation Strategy for Enhanced Water Sources in Machakos Town*. A Research Thesis Submitted for Award of Master of Arts Degree, Environmental Planning and Management at the Department of Geography and Environmental Science at the University of Nairobi, Kenya.

Aroka, N. 2010 *Rainwater Harvesting in Rural Kenya; Reliability in a Variable and Changing Climate*. Master's Thesis, Physical Geography and Quaternary Geology, at the Department of Physical Geography and Quaternary Geology, Stockholm University.

Badiru, A. & Omitaomu, O. 2007 *Computational Economic Analysis for Engineering and Industry*. CRC Press, Boca Raton, FL.

Baek, C. W. & Coles, N. A. 2011 Defining reliability for rainwater harvesting systems. In *Presented at the 19th International Congress on Modelling and Simulation*, Perth, Australia, 12–16 December 2011.

Black, J., Maimbo, M., Alex, O., Kipruto, C. & Meshack, N. 2012 *Rainwater Harvesting Inventory of Kenya: An Overview of Techniques, Sustainability Factors, and Stakeholders*. World Agroforestry Centre (ICRAF), Nairobi, Kenya.

Chamwada, A. 2019 *Why the Government Is Investing Heavily in Water Pans for Irrigation KTN News for 16th, May, 2019*. Available from: https://www.youtube.com/watch?v=Y2_JGlQK8-k.

Dirk, R. 2013 *Frequency Analysis of Rainfall Data*. International Center for Theoretical Physics.

FAO 1993 *Field Measurement of Soil Erosion & Runoff*. FAO, Rome, Italy.

FAO 2010 *Manual on Small Earth Dams: A Guide to Siting, Design and Construction*. FAO Irrigation and Drainage Paper, 64. FIAT, PANIS, Viale delle Terme di Caracalla 00153, Rome, Italy.

FAO 2014a *Compendium on Rainwater Harvesting for Agriculture in the Caribbean Sub-region*. Viale delle Terme di Caracalla 00153, FAO, Rome, Italy.

FAO 2014b *Feasibility Study of Rainwater Harvesting for Agriculture in the Caribbean Subregion*. FIAT, PANIS, Viale delle Terme di Caracalla 00153, Rome, Italy.

Fenu, G. & Malloci, F. M. 2020 DSS LANDS: a decision support system for agriculture in Sardinia. *HighTech and Innovation Journal* **1** (3), 129–133.

Fox, P., Rocksrom, J. & Baron, J. 2005 Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya. *Agricultural System* **83**, 231–250.

Gachene, C. K. K. & Kimaru, G. 2003 *Soil Fertility and Land Productivity – A Guide for Extension Workers in the Eastern Africa Region*. Technical Handbook No. 30. Regional Land Management Unit (RELMA)/Swedish International Cooperation Agency (SIDA), Nairobi, Kenya.

Hatibu, N. & Mahoo, H. 1999 Rainwater harvesting technologies for agricultural production: a case for Dodoma, Tanzania. In: *Conservation Tillage with Animal Traction* (P. G. Kaumbutho & T. E. Simalenga, eds). A resource book of the Animal Traction Network for Eastern and Southern Africa (ATNESA). Harare, Zimbabwe, 173p. Available from: http://www.atnesa.org.

Ibraimo, N. M. 2007 Rainwater harvesting technologies for small scale rainfed agriculture in arid and semi-arid areas. *International Journal of Education and Research* **1** (6), 1–3.

IPCC, Climate Change 2014 *Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 688. Sweetbriar Brook, Ampthill, Storbritannien, p. 66.

Kahinda, J. M., Rockström, J., Taigbenu, A. E. & Dimes, J. 2007 Rainwater harvesting to enhance water productivity of rainfed agriculture in the semi-arid Zimbabwe. *Physics and Chemistry of the Earth* **32**, 1068–1073.

Karara, G. K. 2018 *Assessment of Rainwater Harvesting Potential for Irrigation in Nyeri, Kenya*. A Thesis Submitted for Award of MSc, Soil and Water Engineering in the School of Environmental and Biosystems Engineering at Jomo Kenyatta University of Agriculture and Technology.

Kenya Rainwater Association 2010 Annual report.

Kiggundu, N., Wanyama, J., Mfitumukiza, D., Twinomuhangi, R., Barasa, B., Katimbo, A. & Kyazze, F. B. 2018 Rainwater harvesting knowledge and practice for agricultural production in a changing climate: a review from Uganda's perspective. *Agricultural Engineering International: CIGR Journal* **20** (2), 19–36.

Kimani, M. W., Gitau, A. N. & Ndunge, D. 2015 Rainwater harvesting technologies in Makueni County, Kenya. *Research Inventory: International Journal of Engineering and Science* **5** (2), 39–49.

Li, F., Cook, S., Geballe, G. T. & Burch Jr, W. R. 2000 Rainwater harvesting agriculture: an integrated system for water management on rain fed land in China's Semi Arid areas. *AMBIO: A Journal of the Human Environment* **29** (8), 477–483.

Mati, B. M., Malesu, M. & Oduor, A. 2005 *Promoting Rainwater Harvesting in Eastern and Southern Africa, the RELMA Experience*. Working paper, Nairobi.

Matiti, N. S. 2018 *Evaluating Performance of Rainwater Harvesting Technologies in Mwingi Central Sub-county Kenya*. A Research Thesis Submitted for MSc, Environmental and Biosystems Engineering in the School of Environmental and Bio Systems Engineering at the University of Nairobi, Kenya.

Mburu, B. K., Biu, J. & Muriuki, J. N. 2015 Climate change adaptation strategies by small-scale farmers in Yatta District, Kenya. *African Journal of Environmental Science and Technology* 9 (9), 712–722. doi:10.5897/AJEST2015.1926.

Mekdaschi Studer, R. & Liniger, H. 2013 *Water Harvesting: Guidelines to Good Practice*. Centre for Development and Environment (CDE), Bern; Rainwater Harvesting Implementation Network (RAIN), Amsterdam; MetaMeta, Wageningen; The International Fund for Agricultural Development (IFAD), Rome, Italy.

Moges, G., Hengsdijk, H. & Jansen, H. C. 2011 Review and quantitative assessment of ex situ household rain water harvesting systems in Ethiopia. *Agricultural Water Management* 98 (8), 1215–1227. http://dx.doi.org/10.1016/j.agwat.2011.03.009.

MoWI 2005 *Practice Manual for Water Supply Services in Kenya*. Ministry of Water and Irrigation. Available from: https://cae.uonbi.ac.ke/sites/default/files/cae/cae/Water%20Design_Manual_2005.pdf.

Mulwa, R., Rao, K. P. C., Gummadi, S. & Kilavi, M. 2016 Impacts of climate change on agricultural household welfare in Kenya. *Climate Research*. 67, 87–97. doi:10.3354/cr01357.

Munyao, R. M. 2014 *Assessment of Small-scale Water Harvesting and Saving Technologies and Their Application in Mitaboni Location, Machakos County*. A Research Thesis Submitted for MSc, Community Development in the School of Environmental Studies at the Kenyatta University, Kenya.

National Irrigation Board 2019 Available from: https://nib.or.ke/projects/flagship-projects/household-irrigation-water-storage-programme.

Ndomba, P. M. & Wambura, F. J. 2010 Reliability of rainwater harvesting systems in suburbs. A case study of Changanyikeni in Dar es Salaam, Tanzania. *Nile Basin Water Science & Engineering Journal* 3 (3), 73–83.

Ngigi, S. N., Savenije, H. H. G., Rockstro, J. & Gachene, C. K. 2005 Hydro-economic evaluation of rainwater harvesting and management technologies: farmers Õ investment options and risks in semi-arid Laikipia district of Kenya. *Physics and Chemistry of the Earth* 30, 772–782.

Njuguna 2014 *Utilization of Rain Water Harvesting and Appropriately Designed Drip Irrigation Systems to Improve Crop Production for Small Holder Farmers in the Semi-Arid Area of Maai-Mahiu in Nakuru County (Kenya)*. Thesis Submitted for MSc, Irrigation Problems in Developing Countries at the Università Degli Studi di Firenze, France.

Nolan & Lartigue 2017 Evaluation of the performance of rainwater harvesting systems for domestic use in Tlalpan, Mexico City. *Civil Engineering Journal*. doi:10.28991/cej-2017-00000080.

Onyango, S. 2017 *Kenya Launches National Program to Harvest Rainwater*. Available from: http://blog.worldagroforestry.org/index.php/2017/05/10/kenya-launches-national-program-to-harvest-rainwater.

Qin, Y., Huang, Z., Yu, Z., Liu, Z. & Wang, L. 2019 A novel buffer tank to attenuate the peak flow of runoff. *Civil Engineering Journal*. 5 (12), 2525–2532.

Rozaki, Z., Senge, M., Yoshiyama, K. & Komariah, K. 2017 Feasibility and adoption of rainwater harvesting by farmers. *Reviews in Agricultural Science* 5. doi:10.7831/ras.5.56.

Senkondo, E. M., Msangi, A. S. K., Xavery, P., Lazaro, E. A. & Hatibu, N. 2004 Profitability of rainwater harvesting for agricultural production in selected semi-arid areas of Tanzania. *Journal of Application Irrigation Science* 39 (1), 65–81.

Stec, A. & Martina, Z. 2019 An analysis of the effectiveness of two rainwater harvesting systems located in Central Eastern Europe. *Water* 2019 (11), 458.

Thome, J. N. 2005 *Evaluation and Design of Runoff Storage Systems for Supplemental Irrigation in Laikipia District, Kenya*. MSc Thesis. Department of Environmental and Biosystems Engineering, University of Nairobi, Kenya.

Verchot, L. V., Van Noordwijk, M., Kandji, S., Tomich, T., Ong, C., Albrecht, A. & Palm, C. 2007 Climate change: linking adaptation and mitigation through agroforestry. *Mitigation and Adaptation Strategies for Global Change* 12 (5), 901–918.

Vincenza, N., Liuzzo, L. & Freni, G. 2016 Reliability analysis of rainwater harvesting systems in southern Italy. *Procedia Engineering*. 162, 373–380. 10.1016/j.proeng.2016.11.077.

Wachira, F. W. 2013 *Assessment of Rainwater Harvesting Practices, Cropping Systems and Productivity in Smallholder Farms in Laikipia Central District*. A Thesis Submitted for Award of MSc, Agricultural Resources Management in the School of Agriculture at University of Nairobi, Kenya.

Wanyonyi, J. M. 1998 *Possibilities and Challenges in Rainwater Harvesting*. KBC Radio English Service Water and Society Program. Available from: https://www.cpatsa.embrapa.br>catalogo>doc>strategy>1_6_Julius_Wanyonyi.