Rainwater harvesting knowledge and practice for agricultural production in a changing climate: A review from Uganda's perspective

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Abstract: With a changing climate in Uganda, rainfall distribution patterns have become more irregular over time and space. Excess water during rainy season is causing runoff, soil erosion, nutrient depletion and crop damage which reduces the productive capacity of land, while on the other hand, prolonged droughts during the crop growing period have become common occurrences. Additionally, pastoralists lose livestock during the dry period each year in the Cattle Corridor of Uganda due to water shortage and lack of forage. It thus remains difficult to achieve the agricultural development targets identified in the National Development Plan for Uganda, without addressing regular incidences of adverse impacts of climate change. Currently there are no well explained approaches which can contribute to adoption of technologies like rainwater management systems which are crucial in enhancing crop yields and livestock production during periods of water shortage. The overarching objective of this paper was to carry out an assessment of the status, performance, and scope for improving rainwater harvesting (RWH) for small-scale agriculture under local conditions. Accordingly, research gaps in RWH technologies were identified and documented to inform future studies. The research was carried out in the semi-arid areas of Nakasongola, Rakai, and Hoima Districts characterized by crop-livestock dependent livelihoods. Findings show that RWH technologies could enable smallholder farmers and agro-pastoralists to become more resilient to increasing climate variability and climate change by conserving soil and water thus increasing food production and enhancing food security. Small-scale irrigation systems have enabled farmers to adapt to drought challenges by enhancing crop yields and allowed farmers to target for higher market prices usually associated with the effects of drought. However, there are challenges including threats to sustainability of such established systems because of lack of community participation in systems' monitoring and maintenances, and vandalism, and some systems require high investment costs.

Keywords: rainwater harvesting, smallholder, pastoralists, climate change adaptation, food security, crop production, livestock production

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1 Introduction

Much of Africa's economic growth and the livelihoods of its population are highly dependent on climate sensitive sectors, and most especially agriculture and water (CDKN, 2014; Cooper et al., 2008; MWE, 2016). However, the impacts of climate change are amplifying stress on agricultural systems and water availability (IPCC, 2014). In Uganda, climate variables especially rainfall and temperature directly and indirectly impact on agriculture and water sectors which in turn affects economic growth and the livelihoods of the poor. Climate is already changing in the country with

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temperatures having increased by 0.8^{o}C to 1.5^{o}C over a period 1900-2000 and are projected to increase by approximately 1.5^{o}C as early as 2030 and up to 5^{o}C by 2080 (MWE, 2016). The change in climate has been characterised by frequent and severe droughts, heat waves, storms, floods and other climate extremes that are causing severe water stress, and reduced agricultural productivity in a country which is dependent on subsistence rainfed agriculture with irrigated agriculture comprising only 0.1% of total cultivated land (FAOSTAT, 2012; OECD, 2012; World Bank, 2012). The situation is likely to worsen with the projected changes in climate, where temperatures will increase significantly and rainfall totals will reduce as well as rainfall becoming more erratic. In such circumstances, one of the best way to meet the food requirement of the increasing population is ensuring high crop yields by adapting to the impacts of climate change using the best rainwater management systems (Yosef and Asmamaw, 2015). Climate variations and changes have had measurable impacts on agricultural production, which has caused farmers to adopt new practices (Zizinga et al., 2015). Policy makers and scientists have tried to reverse the negative impacts of climate change which is growing as a central development challenge threatening to undermine the adaptation progress and efforts (Zizinga et al., 2015). Sub-Saharan Africa (SSA) countries will suffer most devastating impacts of climate change because of low technological and institutional capacity to adapt to rapid changes in climate (Urama and Ozor, 2010).

Whereas Uganda has registered remarkable economic growth of above 3% in the recent years, one key setback remains the persistent climate shock and stress related food shortages and acute poverty often experienced in many parts of the country (Owino et al., 2014). The current food production levels cannot match the current population growth rate of 3.4%. This situation is partly attributed to occasional poor crop harvests due to erratic rainfall patterns characterised by droughts (Mubiru, 2010) which have a very significant impact on the predominantly rainfed subsistence farming practiced by majority of the farmers (USAID, 2016). Although, Uganda’s agriculture is mainly rainfed but most of the land is suitable for irrigated agriculture (Wanyama et al., 2017). It is projected that about 70% or more of the population live in rural areas and they mostly depend on the rainfed agriculture (Mugerwa, 2007). According to Dinar et al. (2008), poverty will exacerbate due to adverse climate change impacts on agricultural sector, when no proper climate change adaptation and coping practices are put in place. Additionally, prolonged droughts have caused pastoralists to lose stock during the longer dry periods (December to March) that are increasing in frequency and intensity each year, in the Cattle Corridor leading to water shortages and inadequate forage (Few et al., 2015). It remains difficult to achieve the agricultural development targets identified in the National Development Plan (NDP II) 2015–2020 of Uganda, without mitigating the adverse impact of climate variability and changes. With the rise of food market prices and increased knowledge about productive sustainable land and water management systems, these farmers have the capability to self-sustain themselves with enough food or even be food exporters (Mzirai and Tumbo, 2010).

The development of irrigation and agricultural water management technologies have the potential to improve productivity and reduce vulnerability to climate changes/ variability. Rainwater harvesting (RWH) is a prehistoric practice and still forms an integral part of many domestic and farming systems worldwide most especially in arid and semi-arid regions. This is because of the intermittent nature of rainfall events which, obviously cannot be managed (Ibraimo and Munguambe, 2007). Rainwater harvesting will therefore continue to be an adaptation strategy for people living in areas with high rainfall variability, both for domestic supply and to enhance crop, livestock and other forms of agriculture. The major aim of RWH in Supplementary Irrigation is to collect runoff from areas of surplus or where it is not used, store it and make it available, where and when there is water shortage. Such water harvesting enables water availability by buffering and bridging drought spells and dry seasons through storage (Mekdaschi and Liniger, 2013).

The considered view is that unlocking the potential of small-scale rainfed agriculture requires higher investments in better rainwater management facilities.

Developing proper management of irrigation practices and agricultural water can improve food productivity and also mitigate the impacts of climatic change on agriculture (Yosef and Asmamaw, 2015). The most executable irrigation alternative is supplementary irrigation which complements rainfall in periods of water scarcity or stress at sensitive plant growth stages. The water supply sources for supplementary irrigation are rainwater harvesting systems including farm ponds, valley tanks and dams. This therefore shows that rainwater harvesting is one of the most important means which is practiced to increase agricultural productivity and also provide source of water supply in drought prone areas (Yosef and Asmamaw, 2015). RWH practices involve collecting, storing, and conserving rainwater or runoff for domestic, productive and future uses (Ibraimo and Munguambe, 2007; Ngigi, 2003b; URWA, 2013). The technique is simple and low-cost that requires minimum specific knowledge (Boers and Ben-Asher, 1982; Worm, 2006) to establish depending on the capacity and offers many benefits. RWH is a growing technique practiced to deal with water shortages for household needs and agricultural production (Baguma and Loiskandl, 2010; Biazin et al., 2012; Ibraimo and Munguambe, 2007).

There have been efforts by the Government of Uganda and Development Partners to invest in RWH technologies for livestock watering (valley tanks and dams) over the years, but there is still more demand for these structures due to population growth and failure of the RWH systems due to climate variability. Most water stressed areas do not essentially lack precipitation, the problem is absence of collecting and conserving runoff water technologies. Excess rainwater during the rainy season provides an opportunity for rainwater harvesting to meet crop water requirements during periods of prolonged dry spells. There are various RWH technologies, some of which are traditional with benefits that have been verified for increasing agricultural production at reasonable costs (Röckstrom, 2000). However, there has been little progress in replication of these technologies in other regions (Mugerwa, 2007). Currently, Uganda lacks well explained approaches which can contribute to the adoption of technologies like rainwater management systems, which are known to be crucial in enhancing crop yields and livestock production. Thus, it is very essential to explore hindrances which have affected the progress of adopting rainwater harvesting technologies and their management practices. This study explores the hindrances that have affected the progress of adopting rainwater harvesting technologies and their management practices in Uganda. The study documents rainwater harvesting technologies for in-situ soil moisture enhancement, livestock watering and small-scale irrigation, with strategies of how to use the technologies to copy up with the vagaries of climate change/variability and subsequently enhance agricultural productivity.

2 Methodology

The study was mainly composed of review of literature complimented by experiences of farmers in the dry areas of Nakasongola, Rakai, and Hoima Districts. Similarly, research gaps in RWH technologies were analyzed and documented to inform future studies.

2.1 Desk review and consultations

A desk review was conducted to document available rainwater harvesting systems in Sub-Saharan Africa, and practices, all which were scaled down to Uganda. Opportunities and challenges were identified in the literature and reported. In addition, different districts were visited to check if the RWH systems reported in literature are similarly practiced, and compare if there are new innovations introduced by the local communities. Challenges and research gaps with each RWH system in these districts were also identified and documented. From the desk review and case studies, different research gaps were identified in the RWH technologies and small-scale irrigation that can be bridged by future studies. Three districts of Nakasongola, Hoima and Rakai were selected to serve as the case studies for this study. Based on lessons and challenges research gaps were developed.

2.1.1 Literature selection for review

Relevant literature which speak to climate change adaptation strategies through use of RWH systems in Sub-Saharan Africa (SSA) were selected. Only literature reporting findings in this region was considered because Uganda is among the countries found in SSA and the practices might almost be similar. But also finding out if there are different practices done which are lacking in Uganda which could be adopted or recommended.

2.1.2 Consultations in selected study areas

Regions known for using RWH systems for agricultural production in Uganda were selected. From each of the districts visited, RWH systems are being used as an adaptation measure for climate change and all systems were documented. Lessons from the success and failures of each systems were also identified. RWH systems, lessons, challenges and successful stories from the case studies were compared to those reported in literature review. Information was collected through interviewing and observations within each district where the case studies was considered.

2.2 Study areas

Three study areas were selected including Hoima, Rakai and Nakasongola districts as shown in Figure 1. Nakasongola district is one of the districts in the Cattle Corridor of Uganda, and comprises of cattle keeping communities where a number of valley dams have been constructed by the Government and development partners to boost livestock production. Other two districts are known for crop production and it is where some of the projects on supplementary irrigation for proper crop growth have been demonstrated. Rakai district has a project where farmers are trained to use RWH systems for supplementary irrigation for tomato and green pepper growing. Hoima district is also having an ongoing project which focusses on empowering women farmers through vegetable growing with use of RWH technologies for crop irrigation, which is a collaboration between Makerere University and National Agricultural Research Organization (NARO).

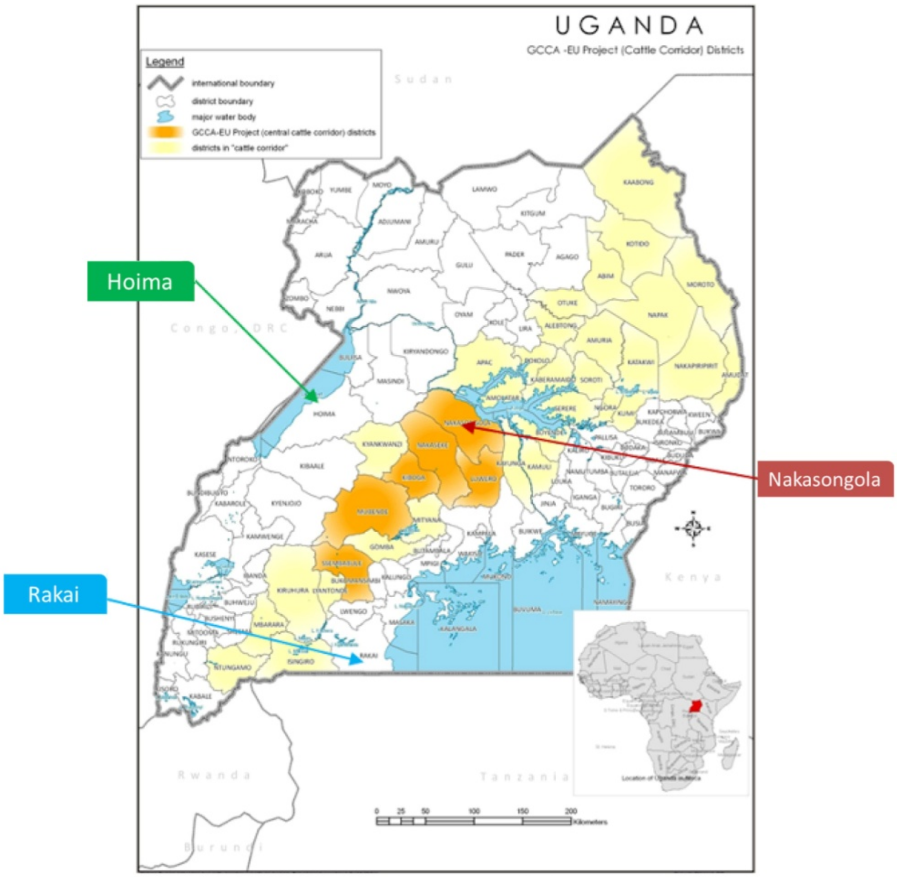

Figure 1 A map of Uganda showing three study areas used for case studies

3 Scope of RWH systems and techniques for agricultural production in SSA

3.1 Categorization of existing RWH systems

Rainwater may be harvested from roofs, ground surfaces as well as from ephemeral watercourses. There are four basic components involved in rainwater harvesting system, (1) catchment or collection area, (2) runoff conveyance system, (3) storage component and (4) an application area. RWH technologies comprises of in-situ and ex-situ types depending on how rainwater is collected and stored. Ex-situ systems collect water from rooftops, land surfaces, steep slopes, road surfaces, rock catchments and stored in tanks. In-situ technologies are strategies undertaken through soil management practices to improve rainfall infiltration and reduction of surface runoff.

3.1.1 In-situ RWH systems

In-situ RWH is referred to as water conservation methods, conservation tillage, runoff farming including rainwater storage systems for supplementary irrigation and application of direct runoff, diversion of floods and spreading systems, small external catchments, and micro catchment systems (Ngigi, 2003b). Yosef and Asmamaw (2015), also explained in-situ methods as those which aim at storing water within the soil profile by trapping or holding rain where it falls. In this way, the movements of rainwater runoff are concentrated where water is most wanted. The primary purpose of in-situ RWH systems is to reduce soil erosion, improve rainfall infiltration and conservation in the soil profile (Bossio and Geheb, 2008). In-situ RWH helps in reserving soil water within rhizosphere where plant roots efficiently take up water and this method is very critically needed for moisture stressed areas. In-situ RWH systems help in soil water recharge which enhances crop and vegetation growth, and recharging shallow groundwater aquifers commonly utilized for livestock and domestic uses. These technologies aim at collecting rainfall where it pours in the cropped area or livestock pastures. Most farmers design those systems in the gardens to reduce in-field runoff and soil erosion, also circulate water within the root zone (Röckstrom et al., 2007). The technique has more benefits in the areas receiving high amount of rainfall with good/evenly rainfall distribution throughout the growing season. However, irrigation is not much applicable in most of the semi-arid areas as these reliable sources of water do not exist (Mzirai and Tumbo, 2010). The systems are simple in nature for example bench terraces, ridging, mulching, conservation tillage and manure addition (FAO, 2002). The benefits of in-situ RWH is that they require small investment capital since most systems are implemented on small scale. However, at times farmers have expressed difficulty in accessing labour particularly in digging canals, constructing contour stone barriers and terraces which are often done during rainy seasons. The in-situ systems work efficiently where the water holding capacity of the soil is high and rainfall received is equal to or more than the crop water requirement. The soil moisture content is controlled by the amount of infiltration or deep percolation.

Topography determines the choice of conservation methods. On sloping lands, terraces, vegetative buffer strips and stone lines are used to reduce soil loss from runoff water. Whereas on flat areas mulching and conservation tillage are used. Normally, on relatively flat surfaces, contour bunds and small stone barriers are used to slow down runoff, allowing rainwater to directly infiltrate into the ground. In areas with steep slopes, terraces are made which have been reported to be labour demanding in terms of setting up different soil layers along the hills. Conservation tillage involves soil tillage and later covered with 30% mulch or crop residues which then left in the field throughout the year to maintain soil moisture and avoid water loss by evaporation (Ngigi, 2003b). In the process, both the infiltration rate and soil water holding capacity are increased. The most common practice is conservation tillage which helps in maximizing the amount of soil moisture within the root zone. Because conservation agriculture is not affected by watershed areas and storage capacity, it can be done on any agricultural land (Röckstrom et al., 2007). The small external catchment system is another technology where the runoff is diverted and directly applied in the cropland or garden. A similar system is well used in banana plantations in south western Uganda, where runoff collected from grazing lands, road drainages and gullies is diverted into plantations (Kiggundu, 2002). Micro-catchment systems also utilize direct runoff which is generated within the field and water is concentrated on a single crop like fruit trees, or a garden established along the contour. In Burkina Faso, micro catchment techniques such as improved traditional planting pits (*Zai* pits) are used to restore the degraded land (Mugerwa, 2007).

3.1.2 Management practices of in-situ RWH systems for soil moisture enhancement

- Contour farming and ridging is where cultivation is done on slopes ranging from 3% and above. Contour farming is complemented with the ridges to increase surface roughness to enhance the infiltration of water into the soil.

- Contour bunds are RWH system which consist of small trash, earth or stone embankments, constructed along the contour lines. The embankments trap the water flow behind the bunds allowing deeper infiltration into the soil. The height of the bund determines the net storage of the structure.

Stone mulching is done in Burkina Faso to control soil erosion and conserve moisture (Zougmoré et al., 2000). In Ethiopia, farmers in dry lands use contour furrow at 2-4 m intervals locally known as 'terwah' (Gebreegziabher et al., 2009). The furrows trap the water in the ridges after storm such that the field has pools of retained water for later use by crops instead of losing it as runoff (Biazin et al., 2012). In Ethiopia, traditional ridging and weed control practice called "Shilshalo" is done after four weeks of maize planting (Brhane et al., 2006). Semi-arid areas of Kenya are practicing small-scale conservation tillage with use of ox-drawn rippers to minimize soil disturbance and conserve soil moisture (Liniger et al., 2011). Similarly, farmers in Kenya traditionally form trash lines from crop residues in surface strips along the contour, to mitigate erosion and as well retain fertile soil and maintain soil moisture (Tengberg et al., 1998).

Table 1 Summary of in-situ rainwater management strategies and corresponding management options to improve yields and water productivity

Aim	Strategy	Purpose	Management options
Increasing the availability of plant water	Conserving soil and water	To concentrate rainfall, in form of runoff to cropped area	Bunds, ridges, broad-beds and furrows, micro basins, runoff strips (write about this)
		To maximize rainfall infiltration	Terracing, contour cultivation, conservation agriculture, dead furrows, staggered trenches)
	Managing evaporation	To reduce non -productive evaporation	Dry planting, mulching, conservation agriculture, intercropping, windbreaks, agroforestry, early plant vigour, vegetative bunds

Note: Source: (Röckstrom et al., 2007).

3.1.3 Categorization of in-situ RWH systems

In-situ RWH systems are mostly runoff based and classified into micro-catchment and macro-catchment systems. The runoff based RWH systems include runoff generation either from external catchments or within field. This is subsequently applied either directly into the soil profile or by means of interim storage for supplementary irrigation. Runoff based RWH systems are further classified based on size of catchments and runoff storage and/or application. This classification is dependent on the source of runoff, the methods of managing the water and use of water. In dry lands of East Africa, water pans and earth dams are constructed at community levels to store water mainly for livestock watering and small-scale irrigation (Ngigi, 2003a). Other storage facilities include concrete or mortar lined subsurface tanks, excavated pits or ponds used for both domestic and livestock water supply. However, according to Ngigi (2003b), their level of investment is relatively high and needs some know-how with regards to water management. The location of storage reservoirs downstream needs extra consideration to control siltation, seepage and a proper water abstraction system. To some extent, the performance of these reservoirs depends on rainfall distribution within a year. Depending on the size of the catchment, direct runoff application systems can be classified as macro-catchment systems, micro-catchment systems and to some extent as small external catchment. In comparison, macro RWH systems with or without reservoirs have been widely installed than the micro catchments systems.

Micro-catchment RWH systems

Micro-catchment RWH systems are constructed to collect runoff from smaller catchment area within the farm boundary in the range of 10-500 m^2 (Trincheria et al., 2016). The runoff water is usually directed into a type of infiltration enhancement structure and used directly by the crops. Micro-catchment can be easily controlled by the farmer which makes the systems easy to install and replicate. The most commonly applied micro-catchment RWH technologies in Sub-Saharan Africa include pitting, contouring, terracing and micro-basins (Biazin et al., 2012). Some of these technologies have different names depending on the region, and minor modifications in design and use. Elsewhere, micro-catchment RWH systems in Burkina Faso are commonly known as Zai pits, Matengo pits in Tanzania, Tassa system of cropping in Niger and fanya juu terraces found in both Kenya and Uganda (Biazin et al., 2012; Ngigi, 2003a). *Fanya juu* terraces, which are made by digging a trench along the contour, and throwing the soil upslope to form an embankment have been effective in reducing soil erosion in areas with relatively steep slopes (Ngigi, 2003a). In southern Ethiopia, famers use traditional terraces for soil and water conservation (Biazin et al., 2012). Vegetation barriers, use of local grasses, woody species and succulents have reduced soil erosion by 70%-90% in central Burkina Faso (Spaan et al., 2005). Modifications to traditional water management practices have improved performance. For example, in Burkina Faso, farmers adapted Zai pits and increased their depth and also apply compost and manure. It has been found out that application of manure in the pit has increased on the water volumes conserved and supply of nutrients which has supported faster growth and maturity of sorghum (Biazin et al., 2012). Therefore, improvement of water availability and fertility in this area helps to restore the productivity of the desert soils (Reij et al., 2009).

Macro-catchment RWH systems

This technology captures runoff from external catchments and diverts into a storage system for use mostly in the dry season (Biazin et al., 2012; Trincheria et al., 2016). The system comprises of a catchment area (the surface on which runoff is generated), runoff transfer infrastructure (channels, gullies, hard surfaces), the storage structure/reservoir and command area (the area where runoff is utilized) in case of supplement irrigation. Runoff is usually collected from existing paved surfaces and natural slopes, and to a lesser extent from intended built-up structures. The purpose is to use water for production including livestock watering and/or supplementary irrigation during the dry-spells. However, during the prolonged dry spell a portion of the water is used for domestic consumption. Irrigation from macro-catchment systems has eventually achieved recognition as an alternative to conventional irrigation schemes with abstraction from rivers or groundwater aquifers. The most commonly applied macro-catchment RWH techniques encompass lined subsurface tanks (with tarpaulin, bricks, sand and cement mortar, etc.), farm ponds, valley tanks and dams, sand dams and spate-irrigation systems. The commonly used traditional surface RWH reservoirs are disadvantaged by short lifespan after the rainy seasons due to evaporation and seepage losses. Likewise, the initial investment costs (e.g. excavation, lining, etc. for a storage tanks of say 10,000 m^3) would be so huge. Most common macro-catchment rainwater harvesting techniques in countries within Sub-Saharan Africa (Table 2) include traditional open ponds, cisterns, micro-dams, sand dams (Biazin et al., 2012). There is low earth dams (Hafr) in eastern Ethiopia traditionally used for livestock and domestic water supply (Biazin et al., 2012). Somalia has “Caag” system where overland flow or gully is captured behind bunds (Biazin et al., 2012). Seepage is a major problem in water storage within the earthen reservoirs which accounts to 90% of the rainwater harvested (Fox and Rockström, 2003). Covering of rainwater storage tank comes with cost a which discourages farmers to invest in covering/roofing tanks (Ngigi et al., 2005). Ethiopian government has given attention to developing and promoting underground rainwater storage tanks-cisterns in moisture stressed rainfed agro-ecosystems after successful experience in China (Biazin et al., 2012). Farmers use locally available materials (termite-mound earth) to construct cisterns. Sand dams are commonly used in Kenya for domestic water supply and irrigation, and also enhancing groundwater recharge (Hut et al., 2008). Tanzania uses dugout ponds found on the roadsides where soil for road construction has been excavated from. Communities use this water for domestic, livestock and vegetable production (Röckstrom et al., 2007).

Table 2 Summary table of Macro-catchment systems in SSA and major countries where they are practiced

System Type	Description	Storage Capacity (m^3)	Major Countries
Traditional open ponds	Runoff collected from cultivated hill slopes, natural watercourses, footpaths or cattle tracks is stored in un-plastered and open ponds. The stored water is lost due to seepage and evaporation	30-50	Kenya, Ethiopia, Tanzania and Somalia. Mainly In East Africa
Cisterns	Runoff collected from bare lands, cultivated hill slopes or road catchments is guided and stored in underground storage tanks. The cisterns have plastered walls and covered surfaces so not prone to evaporation and seepage. Sometimes has settling basins at the inlet to reduce sedimentation or otherwise regular cleaning is required	30-200	Kenya, Ethiopia, Tanzania, Uganda
Earthen dams (Micro dams)	Larger sized rainwater storage system constructed at communal level around foots of hill slopes to store runoff from ephemeral or perennial rivers. The reservoirs are neither plastered at their walls nor covered on their surfaces. The water is mostly used for supplementary irrigation communally and livestock watering	-	Tanzania, Ethiopia, Botswana
Sand dams	They are constructed to store part of the natural flow in seasonal rivers. The sand carried by the river will settle upstream of the dam and gradually fill the streambed, thus sand will reduce evaporation and contamination of water	-	Kenya and Ethiopia

Note: Source: (Biazin et al., 2012).

3.1.4 Ex-situ RWH systems

Ex-situ systems capture water from areas such as roof tops, land surfaces, steep slopes, road surfaces or rock catchments and store in storage tanks. Storage methods for the captured water include dams, ponds and tanks. Depending on the size of the storage, ex-situ systems can be divided into passive and active harvesting systems. Passive harvesting systems are typically small volume systems (200-400 m^3) that capture rooftop runoff without further treatment. Often the captured water is generally used for household consumption purposes. This type of system is commonly used for residential use because of the size. Active harvesting systems are larger volume systems (4,000-400,000 m^3) that capture runoff from roofs or other suitable surfaces such as terraces and road surfaces. Active harvesting systems provide water quality treatments and use pumps to supply water to a distribution system. While passive systems are usually used by individual households, active systems can be used on a municipal level, thus benefitting the entire community. The collected rainwater can then be stored for direct use or can be recharged into groundwater. One of the example of ex-situ systems in Tanzania is the “charco dam” which has been successful among pastoral communities of South Pare Mountains (Baron, 2009). One “charco” dam can store water for pastoralists with more than 30 head of cattle required for the whole dry season. A “charco” dam has three components: a runoff generating or collection area (rangelands); a conveyance system made up of a network of shallow canals (up to 2 km), and a storage area (excavated pond). Thorny brush wood planted around the dam serves as a barrier to control the access to the reservoir. There has been some more provisions on this dam such as drinking troughs where water is pumped from the reservoir using a treadle or motorized pumps and a storage tank above ground. Primarily water is for livestock watering, but it can be used for domestic purposes and vegetable growing at homestead farms. It is estimated that water volumes stored in the “charco” dam lasts for a period of 2 to 6 months (Baron, 2009).

4 RWH technologies for agricultural production in Uganda

4.1 Application of RWH technologies in crop production

The practiced in-situ systems for agricultural production in Uganda are: micro-pits (0.30 m × 0.30 m), semi-circular bunds (3.2-7.0 m Ø), contour bunds/ trenches (*Fanya juu*) with bunds (0.30-0.60 m deep and 0.45-1.50 m width) (Figure 2a and Figure 2b), contour trenches (0.30-0.60 m deep and 0.40-0.90 m width) and soak away pits (Figure 2c). The length of contour bunds and trenches depends on the length of the fields, which may measure up to 50 m. These structures are used mainly in coffee and banana plantations (Figure 2a) and pasture fields (Kiggundu, 2002) to conserve soil moisture (Table 1), however, lately they have found use in vegetable production. Trenches dug with the soil thrown upwards (*Fanya juu*) are popular in controlling soil erosion since after 2-3 years the land between two trenches level up forming a terrace. To allow water in the trench to infiltrate uniformly and to control erosion, tie bunds with a width of 0.3 m, are constructed at intervals of 2.0 m. The trench embankments are stabilized with grass and nitrogen fixing tree species as recommended by the early adopters of the technology. These technologies have been coupled with good crop husbandry practices in greater Rakai and Mbarara regions which led to enhanced yields in both crops and animals. Households that had adopted the innovations were food self-sufficient and they had surplus food, which was sold to generate income (Ngigi, 2003b). These technologies have made significant impact in reducing soil erosion in semi-arid areas with relatively steep slopes (Ngigi, 2003a).

a. Fanya juu contour bund in a banana plantation b. Tied contour trenches in vegetable gardens c. Soak away pit for banana production

Figure 2 In-situ rainwater harvesting technologies: Crop production (Credits: Kiggundu N.)

4.2 Application of RWH technologies in livestock production

The technologies used include farm ponds, valley tanks and dams. Traditionally, people in drylands have known that water can be found in the valley bottoms during the dry spell. So, the idea of owning ponds has been practiced for many years (Kiggundu, 1998; Kiggundu, 2002). Farmers with large herds of cattle own individual ponds, which supply water for domestic needs as well. However, many of these ponds dry during the long dry spells. Runoff can be collected from natural slopes and collected to the intended built structures or channeled into gardens. The water is also used for supplementary irrigation during dry-spells.

Farmers site the farm ponds in the valley spots that normally get water logged whenever it rains, capturing enough runoff (Figure 3a). The footpaths to the ponds form the delivery channel. In some cases, road runoff is diverted through small channels, which lack silt traps into the pond. These ponds range from 76 to 910 m^3 (Kiggundu and Nakanjakko, 2003) and they are used for supplementary irrigation of crops. However, these ponds are associated with problems like seepage and evaporation losses since they are not lined nor covered to control evaporation. Also, siltation is another problem since the ponds lack silt traps and so when it rains the soils on the embankments erode into the pond reducing on its storage capacity. Consequently, they store water for a short period of time into the dry season. However, farmers have tried to come up with simple strategies to conserve the ponds by planting grass along its embankments, fencing the ponds to keep it safe from animals and also protect the embankments.

Development partners like the Germany Technical Services (GIZ) and GCCA through FAO have assisted farmers in the Cattle Corridor in planning and implementation of self-help projects with priority on valley tanks rehabilitation and construction (Figure 3b). For the self-help projects to work, members of a common ranching block were requested to form groups and declare the numbers of animals he/she has. The numbers of animals were used to estimate the water demands of the community and also know how much each member would contribute to the construction of the valley tank. This was termed as the cost sharing system (Kiggundu and Nakanjakko, 2003). The construction work is carried out using a wheel loader and the design criteria (expound on this) of reservoirs are followed. The capacity of the tanks ranges from 4,000 to 10,000 m^3. Seepage losses are minimized by settling and sealing of reservoir bottom pores when little sediments allowed into the reservoir settles. The tanks are constructed with a delivery system, which comprised a 4 m^3 ferro cement tank built on the embankment. This tank is filled using a fixed semi-rotary pump. The water flowed by gravity to the watering trough is shown in Figure 3b. MWE (2012) reported that 53 valley tanks were constructed in the Financial Year of 2010/11 with capacities ranging from 6000 to 10,000 m^3 at parish levels in the districts of Luwero (9 tanks), Nakasongola (8 tanks), Kyenjojo (1 tank), Rakai (9 tanks), Masindi (8 tanks) and Sembabule district (9 tanks). It has been reported that these valley tanks have greatly improved the water storage for livestock in those respective areas. The Government has also rehabilitated dams as means of increasing water capacities in dry areas. Likewise, new dams and tanks have been constructed to increase water storage for agricultural and multipurpose in many districts of Uganda. There are cases in Karamoja where dams can only hold water for a period of less than three months because of their small capacities. Because of this, the communities are suggesting that the Government should consider constructing bigger dams especially in Napak and Moroto in order to solve the water crisis.

a. Farm pond

b. Valley tank with a ferro-cement tank for domestic water supply and a series of trough for livestock water delivery.

Figure 3 Water supply reservoirs in Mbarara District

4.3 Identified challenges and lessons from the RWH technologies in literature reviewed

4.3.1 Lessons

i. Introducing a RWH technology which has been reported successful in other countries is key. For example, Ethiopian government started to develop and promote underground rainwater storage tanks-cisterns in moisture stressed rainfed agro-ecosystems after successful experience in China (Biazin et al., 2012)

ii. Modifications should be done all the time on in-situ systems to ensure increasing productivity and performance. There was high yield, faster growth and maturity of sorghum in Burkina Faso when farmers modified the “zai pits” by increasing the depth and a swell applying compost and manure (Reij et al., 2009).

iii. Wide spread of RWH techniques help in boosting agricultural production. In-situ systems and ex-situ systems are very essential when a farmer is to practice supplementary irrigation and ex-situ systems are very paramount in livestock production since they avail stored water for livestock watering.

iv. Community participatory approach is very key when introducing any RWH technologies to the target farmers. This creates sense of ownership and makes more efforts to learn and practice it among the community members

4.3.2 Challenges

i. For ponds, valley tanks and dams, the challenges faced by the users are mainly, low turn up by community members for maintenance work, default on user fees by some community members, contamination of water by animals and people, siltation of the reservoirs due to soil erosion, over flooding of the reservoirs, vandalism of the watering troughs/pump and theft of the pump or its accessories, misuse/misappropriation of user fees by some of the water user committee members, denied access to the watering sources by land owners, non-functional user committees, drying up of the valley tanks.

ii. For on-farm runoff water (“in-situ”), the challenges associated with technology included, labour intensiveness of making trenches, high cost of tools, poor maintenance of tools, inadequate knowledge/skills on the technology, existence of stoney or rocky parts within the farm land, intensive soil erosion, frequent clogging of trenches, and destruction of trench embankments by animals.

iii. For small scale irrigation technology, the challenges are mainly: prohibitive costs of the technology e.g. a complete drip systems costs over UGX 70 million shillings per acre, lack of knowledge/skills like on use of the bottle irrigation–the farmers lacked knowledge on how the technology works, lack of knowledge/skills on how to operate and utilize irrigation systems, lack of knowledge on the profitability and return on investment of the technology, scarcity of irrigation technicians, frequent breakdown of some irrigation systems components, and substandard equipment on the market.

5 Case studies on RWH technologies for agricultural production

5.1 RWH and irrigation systems components observed in districts

Rakai district farmers use a motorised pump and locally fabricated sprinkler irrigation with the pipe closed at one end and drilled with small holes (Figure 4a). A flexible pipe is connected at the discharge point of the pump and a suction pump in the excavated pond (Figure 4b). The technology is demonstrated to farmers which involved training on how to excavate water ponds for storage of runoff received from catchment areas. The whole system help the farmers to practice supplementary irrigation on their crops.

In Hoima district, the RWH system used is the excavated underground tank lined with tarpaulin (Figure 5c) and drip and sprinkler irrigation systems (Figure 5a and 5b) which are relatively cheap since their costs are within the income range of most smallholder vegetable farmers. The mode of operation of the drip irrigation system is that water is abstracted from the underground tank using a motorized pump and discharged into an overhead tank and water is let to move through the laid laterals within demonstration gardens under a pressure created by the pressure head. For the sprinkler irrigation system, the discharge pipe is connected to the sprinkler and water is pumped from the underground tank under pressure, thereafter water is sprayed around the garden (Figure 5b).

a. Locally made sprinklers used to irrigate tomatoes b. Petrol pump used c. Irrigated green pepper

Figure 4 Supplementary irrigation of vegetables in Rakai district (Credits: Kiggundu N.)

a. Drip irrigation system set up in tomato demonstration garden b. Sprinkler irrigation system in a tomato garden c. Underground tank lined with tarpaulin

Figure 5 Supplementary irrigation in Hoima district (Credits: Kiggundu N.)

The identified RWH technologies for agricultural production in Hoima and Rakai districts are mainly for crop production through supplementary irrigation. Nakasongola is one of the districts in the Cattle Corridor of Uganda and the available RWH technologies are thus for livestock production. Motorized pumps are used on the constructed troughs to water a big herd of cattle, which abstract water from the nearby valley tank (Figure 6c). Other traditional ways of collecting water from the valley tank, use of opened jerry cans is still practiced. Water is poured in a small watering trough built with earth material from anthills at which animals converge to drink water (Figure 6b).

a. Wanzongi valley tank rehabilitated b. Traditional watering trough c. Animals watering from a concrete trough

Figure 6 RWH system for livestock production

5.2 Crop production in Hoima district

In Hoima district, drip and sprinkler irrigation systems are used to produce vegetables (Figure 5a and Figure 5b). There is unexploited market for vegetables from the emerging hotels, rapid urbanization and the emerging oil and gas industry. The project is being carried out in the peri-urban sub-counties of Bugambe and Busisi in the Mid-western Zone of the district. The project is implemented in collaboration with Makerere University and NARO and peri-urban farmers are engaged because of their proximity to the markets. The project is building on the previous work done in mid-western Uganda to empower smallholder vegetable farmers to be business-oriented thus, increasing their income and food security in line with Uganda’s National Development Plan (2015-2020) and Vision 2040. Women have actively got involved in the project since they have special knowledge about traditional water use innovations and vegetable production. Small scale irrigation systems (Figure 5a, Figure 5b) and RWH technologies (Figure 5c) being used are first tested by Agricultural Engineering and Appropriate Technology Research Centre (AEATREC) in collaboration with Makerere University. Farmers have been trained on how to use the systems and there is increase in vegetable production, and they are able to supply the niche markets. A study in Buswekera village, Busisi division in Hoima has shown that vegetable yields increase by 3 to 5-fold and production sustains in the dry season through low-cost rainwater harvesting and low-head small-scale irrigation. To ensure sustainability on each model farm, there are user committees who oversee the performance of the irrigation systems, and in case of a breakdown of the component, they raise money from individual farmers to either replace or repair. Major component of the irrigation system is the pump which has to undergo monthly maintenance and requires fuel to pump water from underground tank. Well trained individuals on the committees help to troubleshoot problems when there is under performance of the system by conducting regular checkups. But when it’s a major breakdown, skilled labor is acquired using money collected from individual farmers.

5.3 Crop production in Rakai district

Households in areas with erratic rainfall and with incidences of drought but with access to adequate storage rainwater tanks either surface or subsurface or those with ponds can irrigate their crops in the dry seasons. Water can be applied using bottles (drip irrigation), watering cans or motorized pumps. Such simple supplementary irrigation technologies (Figure 4) can enhance household food security and also boost the farmer's income (Kiggundu, 2014). The pump and irrigation pipes used to irrigate the crops can be owned by a group of about five farmers to spread out the initial investment. Farmers come up with an appropriate usage roaster for proper use of the system for improved crop production. Experience from Rakai district shows that farmers can recover the money invested in the technology in a period of two dry seasons (Figure 4). Supplementary irrigation empowers smallholder farmers to venture into a wide range of crops including raising seedlings for crops like coffee, tea and other agro-forest wood species.

5.4 Livestock production in Nakasongola district

Nakasongola district has sub counties such as Kisweramayinda, Kinamura, Kalungi, Nakasenyi, Kanyonyi and Wanzogi where cattle keeping is predominantly practiced. Majority of valley tanks in the area had poor water quality which was unsuitable for livestock production (Figure 7a). Most valley tanks had reduced storage volumes due to siltation from runoff water and collapsing of the reservoir embankments. When farm ponds and valley tanks dry up, due to prolonged drought spells, farmers migrate to places with valley dams (Figure 7b), swamps and shores of Lake Kyoga.

As one of its outreach activities, Makerere University rehabilitated Wanzogi valley tank under WATERCAP Project. As a result, the pastoral community stopped migrating to Lake Kyoga in search of water which had never happened in over 20 years. The 4,000 m^3 rehabilitated reservoir (Figure 6a) was able to water 1,272 heads of cattle as well as availing water for domestic use to the entire community. The techniques of maintaining clean water in the reservoirs and managing the reservoirs was copied by the pastoralists who applied these management strategies on the individual ponds within their farms. The community appreciated the need for having a functional water user community in charge of maintaining the reservoir site and collecting user fee to buy fuel for the pump and paying the landlord where the reservoir was situated. In the past, one herdsman would spend more than two hours to water about 30 animals. With the project 50 animals would be watered in 5 minutes. This has saved farmers time and now they can engage in other income generating activities. These successful stories from Nakasongola affirm that the technology can be easily adopted by other communities. Even if one is to invest money in this technology the investment would be recovered within a period of two years from sale of water from the valley tank given that a fee of UGX 4,000 per animal was charged to water animals from a personal reservoir in one dry season. Nakasongola, a Cattle Corridor district, usually faces water stress challenges, and therefore, interventions involving water harvesting will always produce results. Table 3 summarizes some of challenges and lessons learned.

a. Valley tank with contaminated water in Kalungi subcounty

b. Valley dam near Nakasongola town where pastorlists migrate to water animals in prolonged dry spells

Figure 7 Water sources in Nakasongola district (Credits: Kiggundu N.)

Table 3 Identified challenges and lessons for use of RWH Systems in agricultural production

Location	Purpose	Lessons	Challenges
Rakai district	• Supplementary irrigation of crops with use of water pond and small motorised pump and localised sprinkler irrigation system	• Supplementary irrigation boosts the farmers' income and food security • Involvement of farmers in every project make them feel the ownership which ensures sustainability • Participation of farmers in securing a RWH technology for agricultural production make it easier to pay it off • Use of roaster for allocation of time for system use for each farmer spreads the use of the system in all farmers	• Inconsistences in performance of the systems due to leakages on the pipes and pump breakdowns • Inappropriate usage roaster among the farmers and drying up of the ponds since the storage volumes are small incase of onset of a long drought
Hoima district	• Supplementary irrigation of crops (especially vegetables) with use of lined valley tank with tarpaulin and motorized pump and drip and sprinkler irrigation systems	• For successful project in use of RWH system always initiate it with people with special knowledge about traditional rainwater use • Training of farmers before handing over the implemented RWH system will enable sustainability • Implement systems that will ensure food security and income gains after also evaluating the market niches where farmers can sell the produce	• Breakdown of major irrigation systems such as pumps and laid pipes • Lack of money to perform major breakdowns which results into system failures • Loss of stored runoff due to high temperatures and seepage through worn out tarpaulin lining • Selfishness and non-commitment of farmers fails the RWH technologies for agricultural production • Vandalism from people on built structures through theft and misuse of the components e.g use of valley tank for direct cattle watering • Non-performing elected user committees to monitor conditions of the components, proper use by farmers and conducting maintenance at the incidence of breakdowns
Nakasongola district	• Valley tank rehabilitation for livestock watering	• Active user Committee helps in proper function of the RWH system • Communities will protect the system if it offers a solution to the problems faced before • Good water quality and water availability enhances livestock production • Community participation starts from the feel of ownership of the system • Designing a rainwater storage system to support the community throughout a dry spell takes the implementers to know the actual numbers of cattle that will be walked in for watering	• Reduced storage volumes due to seepage, siltation and collapsing of the embankments and drying up of the valley tanks • Vandalizing the set-up components such as water pumps, watering troughs and theft of the pump accessories • Contamination of water by animals and people, and worst is feeding cattle close to valley tank and end up defecating into water • Non-performing Water User Committees who later causes system failures • Low turn up by community members for maintenance work Default on user fees by some community members and misappropriation of user fees by some of the water user committee members

6 Factors influencing the application of RWH in Uganda

Occurrences of climate variability and changes has caused farmers to use several RWH systems and small-scale irrigation technologies as revealed from different studies. By this way they will be able to cope up with effects of climate related challenges. Water scarcity in all the districts has prompted communities and development partners to put more efforts towards implementing RWH technologies for water supply to serve different purposes, both for livestock and crop production. The benefits of constructed systems are very tangible whereby people no longer walk long distances to fetch water, enough time is devoted for children to go to school and acquire education, and the burden has been lessened from women and children who had responsibility of providing water to their families. The stored water has also been used for supplementary irrigation in the vegetable growing gardens. Because Rakai district is at times struck with drought causing food insecurity, the population needs an adaptation strategy and RWH technology is deemed important. Farmer groups are trained on how to use the harvested rainwater from the water pond to boost crop production by practicing supplementary irrigation. Other factors like sustainability in water access in the communities, RWH systems have proved to be at the milestone in achieving this. The stored water has been a resource for growing crops (vegetables) for the case of Rakai and Hoima districts and watering livestock in Nakasongola. Community participation in implementing, monitoring and evaluating benefits of any RWH system is very important. From the case study in Rakai district it is shown that expansion of RWH and small-scale irrigation systems adoption is very possible only if community members especially on group basis are fully engaged through a participatory approach.

7 Recommendation to increase application of RWH technologies

7.1 Farm ponds, valley tanks and dams technologies

- Training and sensitization of user committees on management (i.e. collection, allocation and controlling) of water user fees
- Improve the attitude of community members towards these water sources (valley tanks and dams) as some members prefer watering their animals from the earthen troughs and are not interested in the general management of the water source.
- Need to match demand with supply and develop strategy for other watering sources in case the reservoir dries up.
- Encourage fencing off of the water sources and planting grass in the inlet waterways to the reservoir. This helps in keeping away animals and people not to contaminate the reservoir and grass helps at trapping sediments that might cause siltation and also it improves on controlling soil erosion.

7.2 On-farm runoff water ("in-situ")

- Regular training and awareness raising for user/community on the appropriate dimensions of the trenches and other in-situ moisture enhancement structure and the general maintenance of these structures.
- There is need to train and retain regularly local artisans that can repair and maintain tools used in the installation of the in-situ structures.
- Encourage fencing off plantations to control animals and other intruders that may damage structures.

7.3 Small scale irrigation technology

- Skills and knowledge are needed by farmers on smart irrigation technology in an era of climate change/variability.
- Design of appropriate irrigation systems which are affordable to the local farmers.
- There is need to train and retain regularly local artisans that can operate and repair irrigation systems.
- Regulation of the imported irrigation system components to ensure that they conform to the desired Country standards.

8 Research gaps

The needs identified through this study can be transformed into research gap studies that can avail solutions on how farmers can adapt to the challenges of climate change. Several challenges are faced by users of RWH and small-scale irrigation technologies in Hoima, Nakasongola and Rakai districts.

i. Contribution of rainwater harvesting (in-situ systems) to moisture retention and crop/fodder yields

The study focuses on quantifying the amount of soil moisture retained by the different RWH technologies and the contribution of this retained moisture on the crop yield/biomass at harvest. This information will be vital in optimizing irrigation water requirement in systems where irrigated agriculture is combined with RWH technologies.

ii. Sustainability of household level rainwater harvesting systems used for gardening in the context of climate change

Need of clear technical guidelines for matching household level rainwater harvesting systems with appropriate small-scale irrigation systems. Information is also needed on economics of rainwater harvesting for sustainable small-scale irrigation.

iii. Impact of climate change on the rainwater harvesting systems and available water resources

Climate change is expected to alter the hydrological cycle resulting in large-scale impacts on water availability. Such information is needed for planning and devising sustainable RWH and irrigation adaptation strategies for smallholder farmers.

iv. Adoption of innovations for sustainable and efficient water harvesting water use

Relevant innovations have been experimented on-station but not tested with smallholder farmers for improving food security and incomes of smallholder farmers amidst a changing climate. Even where innovations are being used, appropriate recommendations are not available. There is a need to demonstrate techniques that are suitable to different Agro-ecological zones.

v. Mapping of the rainwater harvesting potential and utilization in different agro-ecological zones of Uganda

Explore use of satellite products to assess water harvesting potential in remote areas to guide climate change adaptation planning linked to water resources management. This should be backed up with community assessments of water resources and rainwater harvesting systems potential and utilization.

vi. Impact of water harvesting and small-scale irrigation at catchment level

There is need to determine the local impacts of water harvesting and small-scale irrigation innovations on water quality and quantity in small catchments. This should generate clear procedures for water allocation, water recharge and retention at catchment scale.

vii. Sustainable management of rainwater harvesting systems for livestock production.

There is need for sustainable management of livestock watering systems in light of climate change. This calls for development a decision management tools for water usage from the water harvesting systems e.g. valley tanks and valley tank. Clear maintenance operating rules are essential during periods of water shortage.

i. Evaluation of water quality in storage tanks for domestic, livestock and irrigation use

In storage tanks water may be stored for a period longer than a month, to avail water in the dry season. The water quality (chemical, physical, biological, and radiological characteristics of water) can deteriorate over time and this can be associated with the material of the storage tank, the configuration of the structure or the means used to draw water from the tank water. Although DRWH tanks are fitted with covers at the top, small insects, rodents and dust may enter into the water and subsequently compromise its quality. The foreign matter deposited in the tanks many allow growth of micro-organisms that affect water quality for domestic, livestock and even irrigation uses over time.

ii. Social-economic and institutional issues surrounding RWH and small-scale irrigation technologies

Implementation of RWH and small-scale irrigation technologies in Uganda has been carried out with support from different agencies. Site selection for the reservoir, designs, material sourcing, implementation of the structure and management are greatly influenced by the social-economic issues and institutional arrangements of a particular area. There is a need to investigate how these issues affect the adoption, management and sustainability of the infrastructures in a given area.

9 Conclusion

RWH technologies for agricultural production are associated with so many tangible benefits both at a community and national level. In-situ RWH systems have enhanced crop and fodder yields where the systems have been implemented and properly managed. At individual level, farm ponds and valley tanks have been able to supply water for livestock and supplementary irrigation during the dry seasons. Unfortunately, these systems have recorded more failures at a community level due to poor management and vandalism. There has been slow diffusion of the RWH technologies in the different districts of Uganda because of lack of knowledge for people to ensure sustainability of the constructed systems. Although the Ugandan government together with donor partners have tried to invest in the rehabilitation of several livestock watering sources within the cattle corridor, communities are negligent of their responsibilities of managing the systems. Recommendations as derived from the case studies in this study are that to all the stakeholders who plan to extend RWH systems to communities, before any system is implemented, they should understand what system is required and then select the most appropriate one for the target area. Communities should also be properly sensitized about this new RWH system for them to have a general knowledge of how the system works, operated and its future failures such that they are avoided. Sustainability has to be ensured by helping communities to set up competent user communities, train individuals on how to troubleshoot prior to a breakdown and also constant monitoring is needed since most systems have failed due to vandalism, breakdowns, thefts and incompetent user communities.

References

Baguma, D., and W. Loiskandl. 2010. Rainwater harvesting technologies and practises in rural Uganda: a case study. *Mitigation and Adaptation Strategies for Global Change*, 15(4): 355–369.

Baron, J. 2009. *Rainwater Harvesting: A Lifeline for Human Well-being*. Stockholm, Sweden: United Nations Environment Programme and Stockholm Environment Institute.

Biazin, B., G. Sterk, M. Temesgen, A. Abdulkedir, and L. Stroosnijder. 2012. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa–a review. *Physics and Chemistry of the Earth, Parts A/B/C*, 47: 139–151.

Boers, T. M., and J. Ben-Asher. 1982. A review of rainwater harvesting. *Agricultural water management*, 5(2): 145–158.

Bossio, D., and K. Geheb. 2008. *Conserving Land, Protecting Water*. Wallingford, UK: CABI.

Brhane, G., C. S. Wortmann, M. Mamo, H. Gebrekidan, and A. Belay. 2006. Micro-basin tillage for grain sorghum production in semiarid areas of Northern Ethiopia. *Agronomy Journal*, 98(1): 124–128.

CDKN. 2014. The IPCC's Fifth Assessment Report: What's in it for Africa. Available at: https://cdkn.org/resource/highlights-africa-ar5/?loclang=en_gb. Accessed 20 April 2017.

Cooper, P. J. M., J. Dimes, K. P. C. Rao, B. Shapiro, B. Shiferaw, and S. Twomlow. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems & Environment*, 126(1-2): 24–35.

Dinar, A., R. Hassan, R. Mendelsohn, and J. Benhin. 2008. *Climate Change and Agriculture in Africa: Impact Assessment and Adaptation Strategies*. London, UK: Earthscan Publications Ltd.

FAO. 2002. Crops and Drops: Making the Best Use of Water for Agriculture. Available at: http://www.fao.org/docrep/005/Y3918E/Y3918E00.htm. Accessed 18 April 2017.

FAOSTAT. 2012. FAOSTAT Database. Available at: www.faostat.org/. Accessed 21 April 2017.

Few, R., P. Satyal, D. McGahey, J. Leavy, J. Budds, M. Assen, L. Camfield, D. Loubser, M. Adnew, and W. Bewket. 2015. Vulnerability and Adaptation to Climate Change in Semi-Arid Areas in East Africa. Available at: http://www.assar.uct.ac.za/sites/default/files/image_tool/images/138/RDS_reports/EAST-AFRICA/East%20Africa%20RDS%20full%20report%20-%20revised.pdf. Accessed 15 April 2017.

Fox, P., and J. Rockström. 2003. Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel. *Agricultural Water Management*, 61(1): 29–50.

Gebreegziabher, T., J. Nyssen, B. Govaerts, F. Getnet, M. Behailu, M. Haile, and J. Deckers. 2009. Contour furrows for in situ soil and water conservation, Tigray, Northern Ethiopia. *Soil and Tillage Research*, 103(2): 257–264.

Hut, R., M. Ertsen, N. Joeman, N. Vergeer, H. Winsemius, and N. van de Giesen. 2008. Effects of sand storage dams on groundwater levels with examples from Kenya. *Physics and Chemistry of the Earth, Parts A/B/C*, 33(1-2), 56–66.

Ibraimo, N., and P. Munguambe. 2007. Rainwater harvesting technologies for small scale rainfed agriculture in arid and semi-arid areas. Department of rural engineering, faculty of agronomy and forestry engineering, University Eduardo Mondlane, Maputo, Mozambique.

IPCC. 2014. Climate Change 2014: Impacts, Adaptation and Vulnerability. Available at: http://www.hko.gov.hk/climate_change/ed_package/doc/impacts_av.pdf. Accessed 12 April 2017.

Kiggundu, N. 1998. An evaluation and modelling of rainwater conservation and utilization: Case studies of Sipili, Kenya and Mijjwala, Uganda. M. S. Thesis. Kenya: Dept. of Agric. Eng., Univ. of Nairobi.

Kiggundu, N. 2002. Evaluation of rainwater harvesting systems in Rakai and Mbarara Districts, Uganda. GHARP case study report. Nairobi, Kenya: Kenya Rainwater Association.

Kiggundu, N. 2014. Small changes have big effects. *Resource Magazine*, 21(6): 17.

Kiggundu, N., and G. Nakanjakko. 2003. Evaluation of rainwater harvesting systems for livestock production in Uganda: A case of Mbarara district. In *Proc. 11th International Rainwater Catchment Systems Conference*. Texcoco, Mexico, 22–26 September.

Liniger, H. P., R. Mekdaschi-Studer, C. Hauert, and M. Gurtner. 2011. *Sustainable Land Management in Practice – Guidelines and Best Practices for Sub-Saharan Africa*. Rome, Italy: World Overview of Conservation Approaches and Technologies (WOCAT) and Food and Agriculture Organization of the United Nations (FAO).

Mekdaschi, R., and H. Liniger. 2013. *Water Harvesting: Guidelines to Good Practice*. Bern, Switzerland: Centre for Development and Environment.

Mubiru, D. 2010. Climate Change and Adaptation Options in Karamoja. Available at: http://www.fao.org/fileadmin/user_upload/drought/docs/Karamoja%20Climate%20Change%20and%20Adaptation%20Options.pdf. Accessed 7 May 2017.

Mugerwa, N. 2007. Rainwater Harvesting and Rural livelihood Improvement in Banana Growing Areas of Uganda. Available at: http://www.diva-portal.org/smash/get/diva2:23019/FULLTEXT01.pdf. Accessed 5 April 2017.

MWE. 2012. Water and Environment Sector and Performance Report. Available at: http://library.health.go.ug/download/file/fid/1329. Accessed 9 April 2017.

MWE. 2016. Water and Environment Sector and Performance Report. Available at: http://envalert.org/wp-content/uploads 2016/09/SPR-2016_final.pdf. Accessed 10 April 2017.

Mzirai, O., and S. Tumbo. 2010. Macro-catchment rainwater harvesting systems: challenges and opportunities to access runoff. *Journal of Animal and Plant Sciences*, 7(2): 789–800.

Ngigi, S. N. 2003a. *Rainwater Harvesting for Improved Food Security: Promising Technologies in the Greater Horn of Africa*. Nairobi, Kenya: Kenya Rainwater Association.

Ngigi, S. N. 2003b. What is the limit of up-scaling rainwater harvesting in a river basin? *Physics and Chemistry of the Earth, Parts A/B/C*, 28(20): 943–956.

Ngigi, S. N., H. H. Savenije, J. Rockström, and C. K. Gachene. 2005. Hydro-economic evaluation of rainwater harvesting and management technologies: farmers' investment options and risks in semi-arid Laikipia district of Kenya. *Physics and Chemistry of the Earth, Parts A/B/C*, 30(11): 772–782.

OECD. 2012. Organization for Economic Co-operation and Development (OECD) Statistics. Available at: https://stats.oecd.org/. Accessed 16 April 2017.

Owino, A., R. Wesonga, and F. Nabugoomu. 2014. Determining food insecurity: An application of the Rasch Model with household survey data in Uganda. *International Journal of Food Science*, 2014: 1–8.

Reij, C., G. Tappan, and M. Smale. 2009. Agroenvironmental transformation in the Sahel: Another kind of "Green Revolution". IFPRI Discussion Paper 00914. Washington, D.C.: International Food Policy Research Institute.

Rockström, J. 2000. Water resources management in smallholder farms in eastern and southern Africa: An overview. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 25(3): 275–283.

Rockström, J., N. Hatibu, T. Y. Owels, S. Wani, J. Barron, A. Bruggeman, J. Farahani, L. Karlberg, and Z. Qiang. 2007. Managing water in rainfed agriculture. In *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, ed. D. Molden, ch. 8, 315–352. London, UK: International Water Management Institute.

Spaan, W. P., A. F. S. Sikking, and W. B. Hoogmoed. 2005. Vegetation barrier and tillage effects on runoff and sediment in an alley crop system on a Luvisol in Burkina Faso. *Soil and Tillage Research*, 83(2): 194–203.

Tengberg, A., J. Ellis-Jones, R. Kiome, and M. Stocking. 1998. Applying the concept of agrodiversity to indigenous soil and water conservation practices in eastern Kenya. *Agriculture, Ecosystems & Environment*, 70(2-3): 259–272.

Trincheria, J., S. Adhiambi, S. Bila, B. Cuamba, D. Dawit, W. Leal, and M. Wuta. 2016. Fostering the use of rainwater for small-scale irrigation in sub-saharan Africa. *AFRHINET*

Urama, K. C., and N. Ozor. 2010. Impacts of climate change on water resources in Africa: the role of adaptation. *African Technology Policy Studies Network*, 29: 1–29.

URWA. 2013. A Construction Documentation for the Promotion of 3R (Recharge, Retention and Re-Use). Available at: https://www.pseau.org/outils/ouvrages/urwa_a_construction_documentation_for_a_pond_and_a_ferrocement_tank_2013.pdf. Accessed 10 April 2017.

USAID. 2016. Uganda Food Security Outlook October 2015 to March 2016. Available at: www.fews.net/sites/default/files/documents/reports/UG_OL_10_2015_final.pdf. Accessed 20 April 2017.

Wanyama, J., H. Ssegane, I. Kisekka, A. J. Komakech, N. Banadda, A. Zziwa, T. O. Ebong, C. Mutumba, N. Kiggundu, and R. K. Kayizi. 2017. Irrigation development in Uganda: constraints, lessons learned, and future perspectives. *Journal of Irrigation and Drainage Engineering*, 143(5): 1–11.

WorldBank. 2012. World Development Indicators. Available at: https://datacatalog.worldbank.org/dataset/world-development-indicators. Accessed 15 April 2017.

Worm, J. 2006. *AD43E Rainwater Harvesting for Domestic Use*. Wageningen, The Netherlands: Agromisa Foundation and CTA.

Yosef, B. A., and D. K. Asmamaw. 2015. Rainwater harvesting: An option for dry land agriculture in arid and semi-arid Ethiopia. *International Journal of Water Resources and Environmental Engineering*, 7(2): 17–28.

Zizinga, A., M. Tenywa, J. Majaliwa, M. Mugarura, P. Ababo, A. Achom, G. Gabiri, Y. Bamutaze, L. Kizza, and E. Adipala. 2015. Potential climate change adaptation and coping practices for agricultural productivity in the mountain areas of south western Uganda. *Journal of Scientific Research and Reports*, 7(1): 23–41.

Zougmoré, R., S. Guillobez, N. Kambou, and G. Son. 2000. Runoff and sorghum performance as affected by the spacing of stone lines in the semiarid Sahelian zone. *Soil and Tillage Research*, 56(3): 175–183.