Walter Leal Filho
Josep de Trincheria Gomez *Editors*

# Rainwater-Smart Agriculture in Arid and Semi-Arid Areas

## Fostering the Use of Rainwater for Food Security, Poverty Alleviation, Landscape Restoration and Climate Resilience

Springer

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# Preface: Rainwater-Smart Agriculture in Arid and Semi-arid Areas

**Walter Leal Filho and Josep de Trincheria Gomez**

Food insecurity has negative economic impacts, exacerbates poverty and poses today a problem to hundreds of millions in the African continent, especially in rural communities of arid and semi-arid regions (UN 2015). By mid-century, nine billion people will require an increase in food production as per today. Inevitably, competition for energy, land and water will rise with growing food demand (Park 2016). Much of this production will be derived from rural production systems, placing these systems at the heart of the sustainable development agenda (Nicol et al. 2015). However, rainfall variability and insufficient capacity to manage that variability lies behind much of the prevailing poverty and food insecurity in arid and semi-arid areas of sub-Saharan Africa (IWMI 2015) rather to cumulative annual and seasonal rainfall (Nicol et al. 2015; Rockström and Falkenmark 2015). Such irregular patterns result in high risk of drought and intra-seasonal dry spells, which in turn lead to unpredictable and depressed crop yields, perennial food shortages, rampant poverty levels and disruptive conflicts over use and access to existing water supplies (Ngigi 2003). Today, half a billion people in the world face severe water scarcity all year round, especially in sub-Saharan Africa (Park 2016).

The soil is a non-renewable resource, and functional soils are crucial for food production and the resilience to dry spells and droughts in arid and semi-arid areas (FAO 2015a, b, c). In addition, the soil is the foundation for feed, fibre, fuel and medicinal products (FAO 2015b, c). Soil moisture is directly related to food security (FAO 2015b, c), and therefore, improved soil moisture management is

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critical for the development of sustainable agriculture in arid and semi-arid areas (FAO 2015a, b, c). However, the current rate of soil and land degradation in these regions severely threatens the capacity to meet the food and livelihood needs of current and future generations (FAO 2015b, c). Soil management is an integral part of land management and focuses on differences in soil types and soil characteristics to define specific interventions that are aimed to enhance the soil quality for the land use selected (FAO 2015c).

This situation is currently being aggravated by the ensuing climate change and variability (Pachauri et al. 2014), which increases water stress, soil degradation and food insecurity in arid and semi-arid areas (Nicol et al. 2015). It is widely known that Africa is one of the most vulnerable continents to climate variability and change, which is expected to have widespread impacts on African societies and their interaction with their natural environment (Pachauri et al. 2014). Smallholder farmers in arid and semi-arid areas of sub-Saharan Africa often experience total crop failure once every ten years and drastically reduced yields from two to four times during the same time period (Fischer et al. 2009).

The above-mentioned challenges are directly or indirectly water- and soil-related, especially in terms of capturing and storing rainwater when and where it falls, and being able to sustainably preserve and use locally available soil resources (Nicol et al. 2015). In this regard, meeting current and future global food needs requires upgrading agriculture by adopting cost-effective strategies for managing rainwater and soil fertility at a small-scale farmer level (Rockström and Falkenmark 2015).

Rainfed and off-season irrigated agriculture in arid and semi-arid areas of sub-Saharan Africa can be significantly upgraded by means of the implementation of rainwater harvesting and soil management practices (Awulachew et al. 2005; Mutabazi et al. 2005; Mati 2007; Malesu et al. 2012). Thus, a wide variety of traditional and modern technologies and practices for collecting, storing and using rainfall for rainfed and off-season irrigated agriculture (i.e. crops, livestock, fodder, tree production, wood, fibre, oil, medicines) have gained worldwide momentum (Biazin et al. 2012). In addition, numerous and diverse farming approaches promote the sustainable management of soils with the goal of improving soil fertility and agricultural productivity, among others, landscape management, smart agroforestry, agroecology, conservation agriculture and zero tillage farming (Ngigi 2003; FAO 2015b, c). These practices, when coupled with rainwater harvesting management for food security, not only have the potential to eradicate hunger but also to alleviate poverty, restore degraded lands and decrease the vulnerability to climate variability and change (Pachauri et al. 2014; FAO 2015a; Nicol et al. 2015). These set of technologies range from collecting and storing rainwater (i.e. earth dams, groundwater dams, on-farm ponds, road, rock and roof catchment systems), conserving and maximising soil moisture (e.g. mulching, digging pits, terraces, trenches.), to off-season small-scale rainwater irrigation systems (i.e. linking rainwater harvesting and small-scale irrigation by means of low-cost water pumping and water application systems) (De Trincheria et al. 2016).

Due to the immense transformative potential related to the optimisation and maximisation of the natural biophysical capacity of arid and semi-arid areas by means of the collection, storage and reuse of rainfall coupled with soil management, rainwater-smart agriculture places a specific emphasis on the integrated management of rainwater and soil resources coupled with, among others, small-scale off-season irrigation, integrated landscape restoration practices, agroforestry, and prior- and post-harvest and agronomic management practices. It is precisely the innovative and specific use of these rainwater harvesting technologies and practices in an integrated manner in order to foster food security, poverty alleviation and climate resilience which is defined as rainwater-smart agriculture. As a set of practical approaches focusing not only on the optimisation of locally available rainwater and soil resources in arid and semi-arid areas but also their enhancement, this concept integrates the approaches of water- and climate-smart agriculture (e.g. sustainable intensification practices, endogenous drought tolerant crops, sustainable land management, agroforestry, agroadvisory services) (Nicol et al. 2015) but addresses the specific challenges surrounding rainwater and soil resources in arid and semi-arid areas.

Rainwater-smart technologies and practices, as a key component of locally adapted integrated climate-smart agricultural water management strategies especially suited to arid and semi-arid areas, could contribute increasing global production by 41% and close the water-related yield gap by 62% (Jägermeyr et al. 2016; Park 2016). Thus, supplemental and off-season irrigation during dry spells can trigger important positive production shifts (Oweis et al. 1999; Biazin et al. 2012), and rainwater harvesting and soil moisture conservation techniques can double smallholder yields in drought-prone regions while at the same time improving resilience to climate risks (Oweis et al. 1999; Dile et al. 2013). This would be coupled to a diversification of the income-generation activities which would improve the livelihood potential in rural areas and alleviate poverty. Among other positive impacts, this may not only reduce forced rural migration to rural areas but reverse back previous rural migrants. Moreover, this would also offer the opportunity to buffer potential negative climate change and variability impacts in arid and semi-arid regions during the next century (Bacha et al. 2011).

Yet, despite the seriousness of the problems posed by water scarcity and the need for a great use of rainwater-smart agriculture in arid and semi-arid areas, there is a paucity of publications in this field. Therefore, this book is an attempt to contribute towards addressing this gap. It contains a set of papers on rainwater-smart technologies and practices, and serves the purpose of showcasing experiences from research, field projects and best practices in rainwater-smart agriculture, which may be useful or implemented in many regions and countries suffering from water shortages and food insecurity.

Consistent with the need for more cross-sectoral interactions among the various stakeholders working in the field of rainwater management, this book aims to:

- Provide research institutions, universities, NGOs and enterprises in arid and semi-arid areas with an opportunity to familiarise themselves with current works, initiatives and projects in the field of rainwater-smart management;
- Disseminate ideas, experiences and good practice acquired in the execution of projects, especially successful initiatives and good practice across the developing world on rainwater-smart management, but especially from the African continent;
- Introduce methodological approaches and experiences deriving from case studies and projects, which aim to show how rainwater-smart management may be implemented in practice.

To carry out this goal, this book is divided into two parts:

Part 1—general approaches and methods;
Part 2—case studies and field experiences.

We thank the authors for their willingness to share their knowledge, know-how and experiences, as well as the reviewers, who have helped us to ensure the quality of the manuscripts. We hope this book will encourage further initiatives on rainwater-smart agriculture and help to address the many problems posed by food insecurity in arid and semi-arid areas.

Enjoy your reading!
Walter Leal Filho and Josep de Trincheria Gomez

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# Part I
# General Approaches and Methods

# Using Rainwater for Off-Season Small-Scale Irrigation in Arid and Semi-arid Areas of Sub-Saharan Africa: Key Working Principles and Best Practices

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**Abstract** The performance and cost-efficiency of off-season small-scale irrigation in arid and semi-arid areas of sub-Saharan Africa can be optimised by means of off-season rainwater harvesting irrigation management (RWHI), which is a subset of rainwater harvesting technologies and practices that allows concentrating and storing rainwater to be used for off-season small-scale irrigation of high-value crops in arid and semi-arid areas. A RWHI system has three main components, i.e. rainwater/runoff collection catchment, rainwater/runoff storage facility, and a low-cost irrigation system that applies water to the crop area during dry periods. Best practices for RWHI management at household level are upgraded on-farm ponds and/or low-cost roof catchments connected to manual pumping systems and low-cost drip irrigation kits. Total costs for storage capacities of 50–100 $m^3$ range from 1000 to

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3000 USD and present cost-efficiencies of 26–50 USD/m$^3$ of irrigated water. At community level, hillside earth dams, rock catchments, alluvial shallow groundwater, subsurface dams and sand storage dams can be connected to mechanised/ manual pumping systems and low-cost drip irrigation kits. RWHI systems which use subsurface dams made of soil present the highest cost-efficiency (3 USD/m$^3$ of irrigated water). Further, RWHI technologies are clearly site-specific. Therefore, replication and scaling-up needs to strictly consider multi-dimensional physical and hydrogeological suitability factors coupled with the cost-efficiency and specific technical considerations of the technologies and practices. In addition, the technical and financial capability of the beneficiaries coupled with the revenue potential of the RWHI systems plays a crucial role in the replication of RWHI technologies.

**Keywords** Off-season rainwater harvesting irrigation management Rainwater-smart agriculture · Constraints · Cost-efficiency · Scaling-up

## 1 Introduction

Food insecurity has multi-dimensional negative impacts and poses today a severe and widespread problem for rural communities of arid and semi-arid regions at worldwide level in general, and sub-Saharan Africa in particular (UN 2015). By mid-century, at least nine billion people may require a steep increase in food production (Tesfaye et al. 2016). Much of this production may have to be derived from rural smallholder production systems (Nicol et al. 2015). Yet, rainfed agriculture still bears the largest burden of generating food in sub-Saharan Africa (Falkenmark and Rockström 2004). While there are several interrelated factors responsible for poor performance of rainfed agriculture in sub-Saharan Africa, seasonal soil moisture scarcity is a major factor constraining its potential (Mutabazi et al. 2005; Hatibu et al. 2006; Malesu et al. 2012). One of the main causes of soil moisture scarcity in arid and semi-arid areas is rainfall variability (IWMI 2015; Nicol et al. 2015; Rockström and Falkenmark 2015). Thus, irregular rainfall patterns result in high risk of droughts and intra-seasonal dry spells, which in turn recurrently lead to unpredictable and depressed crop yields, perennial food shortages, rampant poverty levels and disruptive conflicts over use and access to existing water supplies (Ngigi 2003), especially during dry periods. Further, rainfall variability, water scarcity, soil degradation and food insecurity are aggravated by climate change (Pachauri et al. 2014). However, these challenges can be cost-effectively alleviated by capturing, storing and reusing as much as locally available rainwater when and where it falls (Nicol et al. 2015; Rockström and Falkenmark 2015). Thus, to efficiently tap into existing rainwater resources in arid and semi-arid areas has an immense transformative potential basically related to the optimisation and maximisation of the natural biophysical capacity of these areas.

In addition, off-season small-scale irrigation can contribute to important agricultural productivity growth with a large potential for profitable smallholder irrigation expansion in sub-Saharan Africa (Oweis et al. 1999; Biazin et al. 2012; Xie et al. 2014). This group of techniques is innovative low-cost and easy-to-maintain technologies which are operated and managed by individuals or in small self-initiated groups (De Fraiture and Giordano 2014). The main objective is to grow high-value, high nutritious and multi-purpose crops and trees during dry periods for direct consumption and/or the local market (Malesu et al. 2006). Off-season small-scale irrigation is already emerging with force in sub-Saharan Africa as there is an increasing number of smallholder farmers that self-engage in off-season small-scale irrigation (De Fraiture and Giordano 2014). Off-season small-scale irrigation can help securing food supply and contribute to the growth of household incomes for a very significant share of the population in sub-Saharan Africa (Rosegrant et al. 2006). Indeed, Bacha et al. (2011) found that the incidence, depth and severity of poverty were significantly lower among those households with access to irrigation. Moreover, off-season small-scale irrigation has the specific advantage of facilitating additional income during dry periods, when income-generation opportunities are usually very low (Malesu et al. 2006; De Fraiture and Giordano 2014; Nicol et al. 2015). In addition, it allows the diversification of agricultural outputs and income activities.

The cost-efficiency of off-season small-scale irrigation in arid and semi-arid areas of sub-Saharan Africa can be optimised by means of the implementation of rainwater harvesting technologies and practices (Awulachew et al. 2005; Mutabazi et al. 2005; Mati 2007; Malesu et al. 2012). Thus, RWHI management is a subset of rainwater harvesting technologies and practices that allow concentrating and storing rainwater to be used for off-season small-scale irrigation of high-value crops in arid and semi-arid areas. Thus, off-season RWHI management is specifically meant to conduct off-season small-scale agricultural activities, especially kitchen gardens, trees and high-value horticultural crops along riverbanks.

However, the use of rainwater for off-season small-scale irrigation in arid and semi-arid areas is not exploited sufficiently. One of the key factors which are contributing to this fact is a lack of specific information and know-how on RWHI technologies and their practicability. Therefore, this chapter aims to introduce and analyse the concept of off-season rainwater harvesting irrigation management in arid and semi-arid areas and showcase best practical experiences in this field of practice.

## 2 Methodology

This chapter defines what off-season rainwater harvesting irrigation management is, explains its key working principles and describes best techniques of application which are based on 3 years of practical experiences and lessons learned in this field of knowledge because of the implementation of the AFRHINET project. The materials and information in this chapter are based on De Trincheria et al. (2017), who describe and analyse in detail best practices for the use of rainwater for off-season small-scale irrigation in arid and semi-arid areas of sub-Saharan Africa.

AFRHINET (www.afrhinet.eu) was a three-year project which focused on fostering the knowledge and use of rainwater harvesting technologies for off-season small-scale irrigation in rural arid and semi-arid areas of sub-Saharan Africa. The AFRHINET project was part of the ACP Science and Technology Programme, an EU cooperation programme which was funded by the European Union and implemented by the ACP Group of States. The actions as part of the project took place in Ethiopia, Kenya, Mozambique and Zimbabwe. The project was coordinated by the Research and Transfer Centre "Applications of Life Sciences" at Hamburg University of Applied Sciences in Germany. The African partners were Addis Ababa University and WaterAid-Ethiopia in Ethiopia, University of Nairobi and Searnet-ICRAF in Kenya, Eduardo Mondlane University in Mozambique and University of Zimbabwe and ICRISAT-Zimbabwe in Zimbabwe. Various relevant contributions to specific outputs of the project have been provided by Dabane Trust (Zimbabwe), ASAL Consultants and Kenya Rainwater Association (Kenya) and MetaMeta (the Netherlands).

## 3 Key Working Principles of Off-Season Rainwater Harvesting Irrigation Management

### *3.1 Off-Season Rainwater Harvesting Irrigation Management*

Rainwater harvesting for off-season small-scale irrigation (RWHI) is defined as a set of technologies and practices that allow concentrating and storing rainwater and runoff from a larger catchment area (i.e. roads, streams, land, rocks and roofs) to be used for off-season irrigation of high-value crops. RWHI management is distinguished from the use of rainwater for supplemental irrigation because it is specifically meant to conduct small-scale agricultural activities during dry periods, especially kitchen gardens, fruit tree production and high-value horticultural crops along riverbanks, mainly by means of the use of macro-catchment RWH technologies connected to a low-cost irrigation system. However, supplemental irrigation entails the application of a limited amount of water to a rainfed crop because rainfall has failed to provide sufficient water for plant growth (Oweis et al. 1999). Similarly, RWHI management is distinguished from spate irrigation systems, which entail the controlled diversion of flash floods from external catchment areas to the crop area to distribute and conserve the moisture within the plants' root zone (van Steenbergen et al. 2010). However, both rainwater for supplemental irrigation and spate irrigation systems have an immense transformative potential and should be implemented always that it is feasible.

RWHI management is predominantly designed to sustain subsistence agricultural activities during dry periods at the smallholder level. It is suited to be practised in arid and semi-arid regions, where rainwater often has an intermittent character. Due to the irregular distribution of rainfall, storage is an integral part of a RWHI system. Water is, therefore, stored directly in surface and/or shallow groundwater reservoirs, either artificially built or naturally available. In addition, the low-cost irrigation component to provide water to the crop area during dry periods has also a pivotal importance. Figure 1 shows a diagram of a RWHI system.

A RWHI system has three main components:

1. Rainwater/runoff collection catchment.
2. Rainwater/runoff storage facility by means of an artificial and/or natural surface and/or underground reservoir, usually around 25–1000 $m^3$.
3. A low-cost irrigation system that applies water to the crop area during dry periods.

The specific set of technologies that can be used to link rainwater to off-season small-scale irrigation range from systems to collect and store rainwater (i.e. on-farm ponds, road, rock and rooftop catchments, earth dams, groundwater dams and shallow groundwater recharge) to off-season small-scale rainwater irrigation systems (i.e. gravity, manual and mechanised pumping systems connected to manual or mechanised water delivery systems) (De Trincheria et al. 2016a). However, major challenges with regard to the storage of water in arid and semi-arid areas are seepage, evaporation and siltation. Table 1 shows the off-season small-scale irrigation potential of relevant macro-catchment RWH technologies that are currently implemented in sub-Saharan Africa. The link with off-season small-scale irrigation comes when these technologies are linked to water pumping and water application systems, among them, buckets, watering cans, drip irrigation kits, pipes, manual pumps or small motorised pumps.

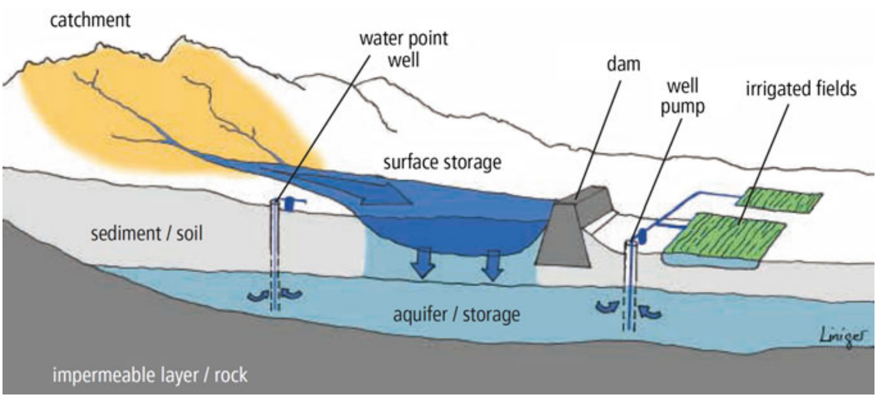


**Fig. 1** Example of a RWHI system showcasing a macro-catchment RWH system linked to a pumping and small-scale irrigation system. *Source* Studer and Liniger (2013)

**Table 1** Potential of macro-catchment RWHI systems to be used for off-season small-scale irrigation

| RWH storage technology | RWHI potential |
|---|---|
| On-farm ponds | +++ |
| Rooftop catchments + on-farm ponds | +++ |
| Road catchments + on-farm ponds | +++ |
| Shallow groundwater recharge with micro-catchment and in situ RWHI systems | +++ |
| Small earth dams | ++ |
| Groundwater dams: subsurface dams and sand storage dams | ++ |
| Rock outcrops + earth dams | ++ |

*Potential* High (+++), Medium (++), Low (+)
*Source* De Trincheria et al. (2017)

In addition, micro-catchment and/or in situ RWH systems show potential for off-season small-scale irrigation if there is a direct or indirect shallow groundwater recharge, which can, in turn, be used as a water source for off-season irrigation during dry periods. Also, these systems inherently increase the soil moisture of the crop rooting zone during wet periods. Thereby, potentially enhancing off-season irrigation during dry periods.

### *3.2 Advantages and Disadvantages*

Table 2 shows an overview of the advantages and disadvantages of RWHI management.

## 4 Best Practices for Collecting and Storing Rainwater for Off-Season Small-Scale Irritation

### *4.1 Upgraded Road Runoff On-Farm Ponds*

On-farm ponds (Fig. 2) have a high potential for small-scale irrigation purposes at the household level (De Trincheria et al. 2017). However, their success has been limited by evaporation, siltation and seepage risks on one hand, and safety and health risks on the other.

An upgraded on-farm pond for off-season small-scale irrigation which takes into account these risks has been developed and promoted by Kenya Rainwater Association (KRA) and is currently being further replicated and scaled-up in cooperation with SEARNET-ICRAF and AFRHINET, among others. The upgrade

**Table 2** Key advantages and disadvantages of off-season RWHI management

| Advantages | Disadvantages |
|---|---|
| *Agricultural productivity and food security* | |
| Securing water for productive use during dry periods<br>Buffering rainfall variability<br>Reducing production risks, thus reducing vulnerability<br>Optimising yield per unit of water<br>Optimising the natural biophysical capacity of arid and semi-arid areas by means of the collection, storage and reuse of locally available rainfall<br>Contribution to the natural recharge of groundwater levels, which have multivariate positive impacts, like the increase of soil moisture and soil fertility | Dependent on the amount, seasonal distribution and variability of rainfall<br>Supply can be limited by storage capacity, design and costs<br>Some RWHI systems may take up productive land<br>High labour requirements for implementation and maintenance |
| *Costs, income and livelihood options* | |
| Off-season high-income production: smallholder farmers with 50 $m^3$ RWHI systems with a low-cost drip irrigation system for horticultural production (250 $m^2$ plot) can earn up to USD 1200/year. With a greenhouse can earn up to USD 2500/year<br>Flexibility and adaptability<br>High-value crops production<br>Alleviating poverty: when adopted at scale<br>Reducing migration to the cities<br>Increase in school performance | Relatively high initial investments for most RWHI systems<br>Low affordability for smallholder farmers<br>Requires access to financing mechanisms<br>Production of fast-growing crops is the only feasible option to take advantage of off-season irrigation water which is usually available for 3 months for most RWHI systems<br>However, these high-value crops are labour-intensive, usually perishable and often pose marketing challenges. This can be addressed by encouraging farmers to form marketing cooperatives |
| *Nutrition and health* | |
| Improvement of nutrition and health through higher crop diversification that supplements the staple diets | Open water reservoirs can be a breeding ground for mosquitos or source of waterborne diseases |
| *Water security* | |
| Lower pressure on conventional water sources<br>Improved water availability for domestic and livestock | Some RWHI systems may reduce the availability of water for ecosystems and/or downstream communities, especially at watershed scale |
| *Resilience to climate variability and change* | |
| Helping to cope with drought, dry spells and rainfall variability | Dependent on rainfall |
| *Technical* | |
| For most RWHI technologies and practices, there are configurations of RWHI systems which can be implemented with low levels of technical and/or engineering skills | Siting and design require technical and engineering skills to ensure proper planning, hydrological assessments, siting/topographical survey, designing, construction |

(continued)

**Table 2** (continued)

| Advantages | Disadvantages |
|---|---|
| | and technical supervision and operation and maintenance |
| *Socio-cultural* | |
| High acceptability of most configurations of RWHI systems, especially for household-based RWHI systems | Acceptance depends on the beneficiary and the perceived notion of risk and profitability by land users<br>Community-based structures can lead to rights issues (upstream–downstream, farmers and herders) and maintenance disagreements<br>Maintenance of communal infrastructures is complex<br>Long-term institutional support is necessary<br>Establishment of operation and maintenance systems for water resource management is inevitable for sustainable use of precious resources |

*Source* De Trincheria et al. (2017) quoting Oweis et al. (1999), Ngigi (2003), Payen et al. (2012), Studer and Liniger (2013), Ngigi et al. (2014) and JICA (2015)

is a runoff storage reservoir with an inverted trapezoidal shape which is connected to a road catchment. In addition, it is lined with an ultraviolet-protected dam liner (thickness: 0.8 mm) to control seepage losses. For small-scale irrigation purposes, a minimum storage capacity of 50 $m^3$ is recommended for top and bottom dimensions of 8 m × 6 m and 4 m × 2 m, respectively, and a depth of 2 m with 1:1 side slope. Different storage capacities for the farm pond can be adopted up to 1000 $m^3$ depending on water demands and the beneficiary's financial capability.

The upgraded on-farm pond is also roofed with an iron sheet or a shade net. The roofing is intended to minimise evaporation losses, mosquito breeding and drowning risk for children and/or domestic animals on one hand, and to protect the dam liner from damage and deterioration from direct exposure to sunlight on the other. On cost-effectiveness, the shade net roofing is about 50% cheaper than iron sheets due to low unit costs per $m^2$ and lighter roofing structure. In addition, the roofing design is further enhanced with fencing with chain link for safety and security reasons.

Safety risks are further reduced by incorporating a manual pump, which enhances the lifting of water from the farm pond into a low-head low-cost drip irrigation system. Moreover, to reduce siltation and improve water quality, a double-chamber silt trap is incorporated. The silt trap is coupled with a screen filter in order to prevent floating debris from entering the farm pond.

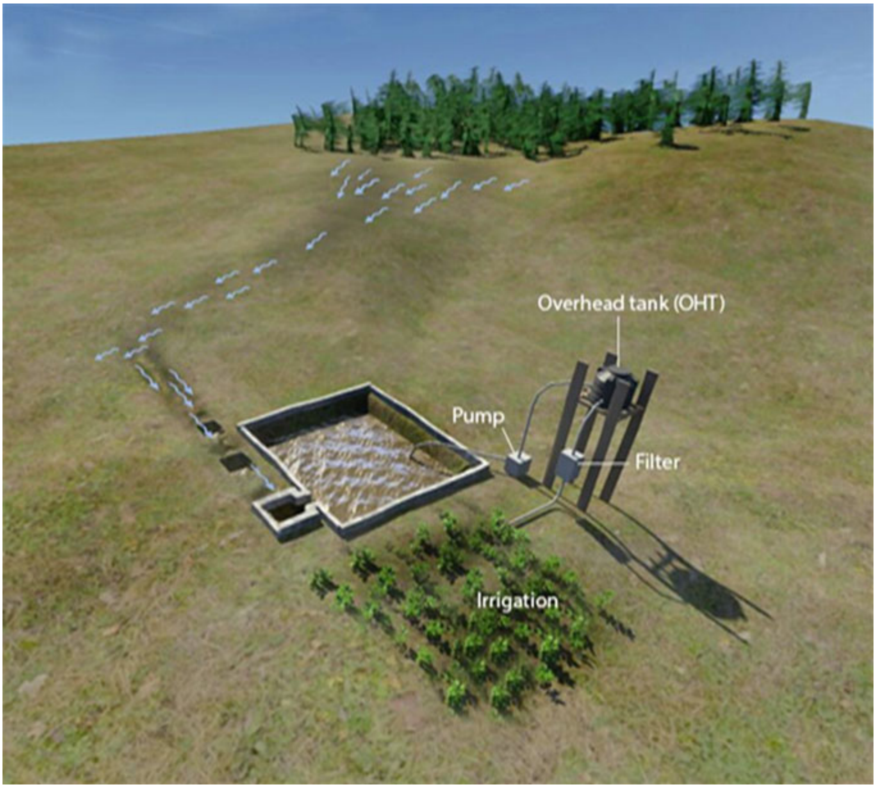


**Fig. 2** On-farm pond system with an off-season small-scale irrigation system. *Source* Pixiniti Studios

## *4.2 Low-Cost Roof Catchments*

Roof catchments are usually only suitable for kitchen gardening due to the high costs and limited storage capacity of water tanks. However, a roof catchment system can also be connected to an on-farm pond, as it is shown in Fig. 3. Thus, this storage system has the potential to further expand their scope and applicability to small-scale horticultural production using drip irrigation and/or greenhouses. Among other factors, on-farm ponds are usually cheaper than tanks. Also, on-farm ponds can potentially store higher volumes of rainwater. Therefore, linking farm ponds with roof catchments can make the whole system more cost-effective. For example, the cost of an upgraded 50 $m^3$ farm pond roofed with a simple metallic structure and shade net is USD 1000.

However, the most cost-efficient type of water tank that can be connected to a roof catchment for micro- and/or small-scale irrigation purposes is a ferro-cement surface tank, as it is shown in Fig. 4. This type of tank can be built with a storage

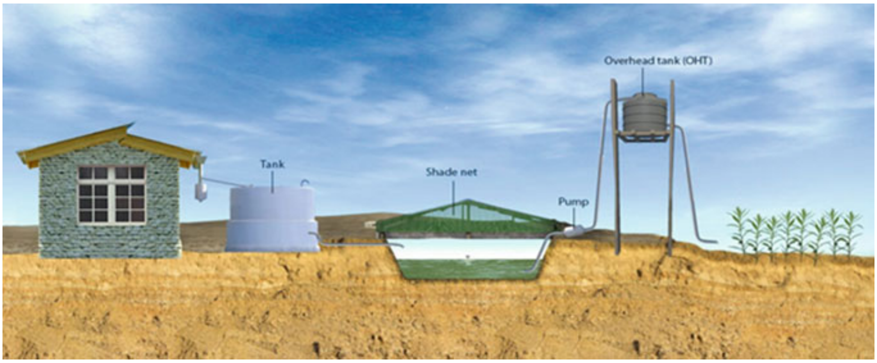


**Fig. 3** Roof catchment system coupled with an on-farm pond and a water tank (optional). *Source* Pixiniti Studios

**Fig. 4** Roof catchment system with ferro-cement tanks. *Photograph* Josep de Trincheria Gomez

capacity of 50 $m^3$ for USD 1500–2000 (Nissen-Petersen 2007) in most situations and conditions.

In addition, a key innovation has taken place in Honduras in the form of elevated impluvium tanks of 23 $m^3$ connected to a small roof with a gutter system that drives water by gravity to a low-pressure drip irrigation system for EUR 1200 (USD 52/$m^3$) (IDE 2017) (Fig. 5). The system has a 2-m height water tank which is built with locally available materials. The impluvium comes with a roof and gutter system. For off-season small-scale irrigation, the impluvium can be used in combination with a

**Fig. 5** Impluvium tank with roof and gutters. *Source* IDE (2017)

drip irrigation kit. The first impluvium system was developed by IDE-Honduras with financial support from Swiss Agency for Development and Cooperation (SDC) and RAIN Foundation.

Also in Honduras, roof catchments are connected to high-density geomembrane bags (1 mm with UV protection) of storage capacity 25 $m^3$ coupled with manual pumps and low-cost drip irrigation kits for USD 910 (Kadet 2017). The system shows potential due to the low costs of the geomembrane bag. However, the bag requires the availability of free space, as it is shown in Fig. 6.

## *4.3 Climate-Resilient Seasonal Sandy Streams and Cost-Efficient Groundwater Dams*

### 4.3.1 Tapping into the Natural Capacity of Alluvial Shallow Reservoirs

If a specific section of a sandy seasonal stream can yield enough water to meet local community needs, to build a groundwater dam is not cost-efficient. Instead, efforts should be directed to implement/improve water abstraction systems that can tap into the natural capacity of the riverbed to yield water during dry periods. This is meant to strengthen in a cost-efficient manner the water access for local communities,


**Fig. 6** Roof catchment connected to a geomembrane bag in Honduras. *Source* Kadet (2017)

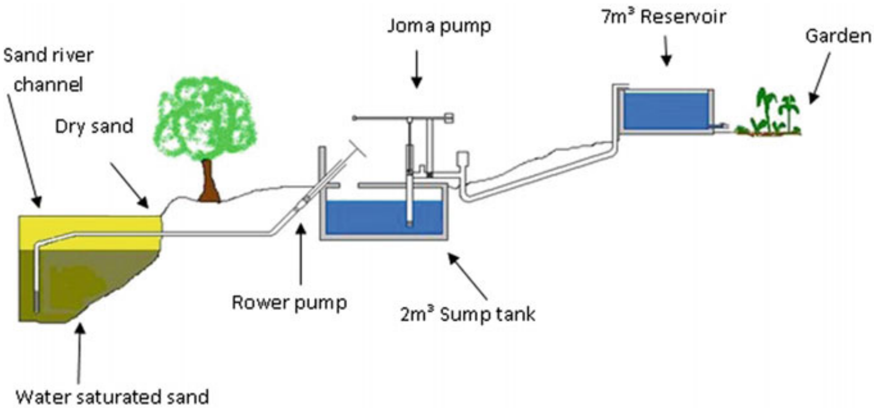


**Fig. 7** Sand abstraction system to tap into natural shallow groundwater in seasonal sandy streams. *Source* Dabane Trust

especially, the link with off-season small-scale irrigation activities. Thus, according to De Trincheria et al. (2017), development agencies should give more attention to low-cost water projects that incorporate upgraded waterholes or hand-dug shallow wells or more sophisticated systems like river intakes or sand abstraction systems (Hussey 2007) (Fig. 7).

### 4.3.2 Implementing Cost-Efficient Subsurface Dams

If the specific section of a seasonal sandy stream cannot yield enough water to meet local community needs, a subsurface dam should always be considered before than a sand storage dam. This is because subsurface dams inherently present higher cost-efficiency levels, higher technical simplicity and higher robustness to erosion and siltation (Nissen-Petersen 2013; De Trincheria et al. 2015, 2016b).

A subsurface dam (Fig. 8) is a small-scale hydraulic retention structure which is built across the width and below the surface of a seasonal sandy stream in arid and semi-arid areas. The structure can be made of concrete, rubble masonry or clayey soil with or without plastic lining. The strengths of subsurface dams revolve around their underground position and the fact that they do not block the surface runoff but shallow groundwater flow.

### 4.3.3 Implementing Smart Sand Storage Dams

A sand storage dam is a subsurface dam whose spillway has been extended above the surface of the riverbed (De Trincheria et al. 2016a). One of the key objectives of a sand storage dam is to artificially increase the volume of sand sediments in the original riverbed, as it is shown in Fig. 9. This is specifically meant to create a sand reservoir that yields enough water to continuously fulfil the water needs of the beneficiaries during the entire dry season.

In order to build smart sand storage dams which are able to perform cost-efficiently, the following recommendations should be followed:

1. To always build the dam wall on an underground dike to reduce costs and gain free storage.
2. The height of the final spillway should allow discharging overflow safely.
3. To use the ALDEV design.
4. The spillway should always be raised by stages of reduced height.
5. To prevent seepage by building the dam wall foundations on murram or clay.

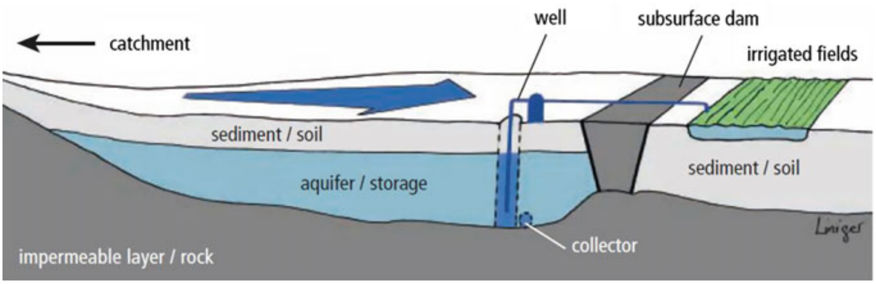


**Fig. 8** Diagram of a subsurface dam. *Source* Studer and Liniger (2013)

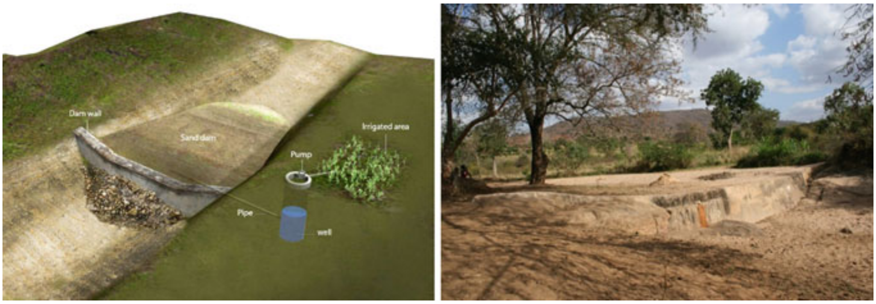


**Fig. 9** Increase in sand sediments on the original riverbed caused by the construction of a sand storage dam: a diagram (left) and a real-life example (right). *Source* Pixiniti Studios. *Photograph* Josep de Trincheria Gomez

## *4.4 Self-replicable Hillside Small Earth Dams*

According to Nissen-Petersen (2015), a semi-circular hillside earth dam is one of the safest designs, as it has a natural spillway at each end of the dam walls which allow runoff to safely overflow. In addition, a hillside dam is relatively easy to construct using a farm tractor with a disc plough to loosen the soil and push it towards the dam wall by driving in continuous circles. Also, an additional advantage of a hillside dam is that the storage capacity can be enlarged every dry season when the water reservoir is dry, until it may hold water throughout the year. Enlargement consists of deepening the water reservoir while using the excavated soil to raise the height of the dam wall and the two spillways. According to Studer and Liniger (2013), it is recommended to plant grass (*Pennisetum clandestinum*) to prevent erosion of the embankment. Also, the earth dam should be fenced with barbed wire to prevent livestock from eroding the wall. Figure 10 shows a semi-circular hillside earth dam. Earth dams have the following components that should be considered in the design of the system: Runoff production factors (i.e. watershed area, surface cover, rainfall distribution and slope, volume of soil to be

**Fig. 10** Small earth dam over the dry season in south-eastern Kenya. *Photographs* Josep de Trincheria Gomez

excavated and water yield of the earth dam) and related structural variables (i.e. spillways, freeboard and crest) on one hand, and evaporation, siltation and seepage losses on the other.

## *4.5 Irrigation-Smart Rock Catchment Systems*

Given the high runoff generation capacity of rock catchments (Fig. 11), the runoff harvested can be used for off-season small-scale irrigation purposes. However, in order to use a rock catchment system for small-scale irrigation, the water reservoir should preferably be a surface reservoir, i.e. an earth dam or a rock dam with or without a roof. Alternatively, a ferro-cement water tank of at least 50 $m^3$ would be required to carry out off-season small-scale irrigation for a single household. In addition, the reservoir can either be constructed within the lowest section of the rock catchment or outside of the rock catchment. If the reservoir is built on the rock catchment itself, then it should be made of stones collected from the vicinity of the rock catchment. The reservoir built on the rock catchment should be sited in order to acquire the highest volume of runoff. If the reservoir is constructed outside the rock catchment, then it can be a small earth dam. Alternatively, a tank can also be built outside the rock catchment. In any case, the size of the earth dam, masonry dam or water tank needs to consider the irrigation water requirements and effective catchment water yield.


**Fig. 11** Rock catchment system. *Photograph* Josep de Trincheria Gomez

# 5 Best Practices on Reusing Rainwater for Off-Season Small-Scale Irrigation

According to Ngigi (2009), the type of irrigation system, i.e. water pumping and application systems, is one of the key factors that determine the success of an off-season small-scale irrigation system. However, other relevant factors are the water source for irrigation (Sect. 3.2), the participation, skills and capacity of the beneficiaries, the market demands, accessibility and the provision of backup services to sustain production (Ngigi 2009).

Several types of energy sources exist for operating water pumps for off-season small-scale irrigation. A manual pumping system is powered by human power (i.e. hand or foot) (Bruni and Spuhler 2010). The capital costs and the discharge of these systems are generally low, and therefore, this type of systems is especially suited for off-season rainwater harvesting irrigation management. Three different types of manual pumping systems show high potential due to their high cost-efficiency and suitability to rural communities in arid and semi-arid areas. The systems are the rope and washer pump, the KickStart MoneyMaker pumps and the so-called Brazilian pump (De Trincheria et al. 2017). In addition, pumping systems based on solar energy and petrol/diesel/kerosene are highly suitable for off-season rainwater harvesting irrigation management (De Trincheria et al. 2017).

Further, the capacity of an irrigation system to apply water uniformly and efficiently to the irrigated area is a major factor influencing the agronomic and economic viability of the system (De Trincheria et al. 2017). Due to their high cost-efficiency and suitability for rural communities in arid and semi-arid areas, low-cost drip irrigation systems (Staufer 2010) (Fig. 12), manual irrigation (Staufer and Spuhler 2010) and low-tech automatic irrigation systems are specifically recommended for off-season rainwater harvesting irrigation management (De Trincheria et al. 2017).

# 6 Discussion

## *6.1 Constraints*

The suitability of each RWHI system should be considered independently based on a multi-dimensional situational analysis coupled with an evaluation of all technically viable and cost-efficient options. Thus, Tables 3 and 4 give an overview of the specific applicability and scalability of RWHI systems.

**Fig. 12** Low-cost LHLCD irrigation system. *Photograph* Josep de Trincheria Gomez

**Table 3** Specific applicability and scalability factors for household-based RWHI technologies

| System | Strengths | Constraints | Applicability/scalability |
|---|---|---|---|
| On-farm ponds + Manual pumping + Low-cost drip irrigation | • High adaptability and flexibility<br>• Relative technical simplicity<br>• Manual construction process<br>• High acceptability, adoption and self-replicability<br>• High suitability with road catchments, which produce large volumes of runoff<br>• High suitability for manual pumping | • Vulnerability to evaporation, i.e. roofing is required<br>• Vulnerability to seepage losses, i.e. dam liner is required<br>• Roofing structures and dam liners are vulnerable to damage, need regular maintenance and repair, and eventually, need to be replaced (approx. 5–10 years)<br>• Vulnerability to siltation, and health and safety risks | • Upgraded on-farm ponds with low evaporation, seepage and siltation losses<br>• Link with road catchments and roof catchments<br>• Access to community-based financing mechanisms supported by business activities<br>• Link with national/ international multi-year funding programs<br>• Access to technical support and spare parts |

(continued)

**Table 3** (continued)

| System | Strengths | Constraints | Applicability/scalability |
|---|---|---|---|
| | and manual water application systems | • Limited yield and supply capacity<br>• Limited irrigable area<br>• High capital investment costs<br>• Low resilience to poor rainfall years<br>• Low natural recharge and low integrated restoration potential at the watershed level | • Adoption of reliable and efficient manual pumping systems<br>• Adoption of low-cost drip and other improved irrigation systems |
| Roof catchments + Manual pumping + Low-cost drip irrigation | • High rainwater collection efficiency<br>• High suitability for individual households<br>• High acceptability and self-replicability<br>• Provision of high-quality water for domestic uses<br>• Low evaporation and siltation risks<br>• Low health and safety risks<br>• Low dependency on the characteristics of the terrain<br>• High suitability for government buildings, schools and churches<br>• High suitability for manual pumping and water application systems | • Limited yield and supply capacity, especially with water tanks and rock dams<br>• Limited irrigable area<br>• High capital investment costs<br>• Low cost-efficiency<br>• Low resilience to poor rainfall years<br>• Leakage risks<br>• Isolated system: no natural recharge or integrated restoration potential at watershed level | • Suitability for kitchen gardening and other income-generating activities at household level<br>• Link with on-farm ponds for off-season micro- and small-scale irrigation<br>• Low-cost ferro-cement tanks should be prioritised<br>• Link with government buildings, schools and churches for off-season small-scale irrigation<br>• Adoption of reliable and efficient manual pumping systems<br>• Adoption of low-cost drip and other improved irrigation systems |

*Source* De Trincheria et al. (2017)

## 6.2 Impacts

The specific impacts of the selected RWHI technologies to collect and store rainwater for off-season small-scale irrigation in arid and semi-arid areas are highlighted in Table 5.

**Table 4** Specific applicability and scalability of community-based RWHI technologies

| System | Strengths | Constraints | Applicability/ scalability |
|---|---|---|---|
| Small earth dams + Mechanised/ manual pumping + Low-cost drip irrigation | • High water yield and supply capacity<br>• High cost-efficiency<br>• Flexible construction process suitable for local communities: manual/animal/ mechanical<br>• Flexible and adaptable designs<br>• High acceptability and adoption<br>• High suitability with road catchments<br>• High natural recharge and integrated restoration potential at the watershed level | • High evaporation losses<br>• High siltation, health and safety risks<br>• High capital investment costs<br>• Low resilience to poor rainfall years and droughts<br>• Conflicts between irrigators and pastoralists<br>• Must be communally owned and managed<br>• Low suitability for manual pumping and manual water application systems | • Link with road and rock catchments<br>• Access to community-based financing mechanisms supported by business activities<br>• Link with national/ international multi-year funding programs<br>• Adoption of reliable and efficient mechanised pumping systems<br>• Adoption of low-cost drip and other improved irrigation systems |
| Natural alluvial aquifers and groundwater dams in seasonal sandy streams + Mechanised/ manual pumping + Low-cost drip irrigation | • High water yield and supply capacity<br>• High cost-efficiency<br>• Resilience to poor rainfall years and droughts<br>• High potential for off-season small-scale irrigation and income-generation activities<br>• High acceptability<br>• High natural recharge and integrated restoration potential at the watershed level | • High capital investment costs<br>• Need to technical and financial external support<br>• High technical complexity<br>• Weak link with gravity-fed irrigation systems<br>• Need of pumping systems<br>• Low self-replicability<br>• Must be communally owned and managed<br>• Low suitability for manual pumping and manual water application systems | • Prioritise natural alluvial shallow groundwater and/or subsurface dams with water abstraction systems<br>• Sand storage dams must be built by stages of reduced height to minimise siltation<br>• Access to community-based financing mechanisms supported by business activities<br>• Link with national/ international multi-year funding programs<br>• Adoption of reliable and efficient |

(continued)

**Table 4** (continued)

| System | Strengths | Constraints | Applicability/ scalability |
|---|---|---|---|
| | | | mechanised pumping systems<br>• Adoption of low-cost drip and other improved irrigation systems |
| Rock catchments + Mechanised/ manual pumping + Low-cost drip irrigation | • Suitable in semi-desert environments<br>• Resilience to poor rainfall years<br>• High rainwater collection efficiency<br>• Provision of high-quality water for domestic uses<br>• Low health and safety risks<br>• Relative technical simplicity<br>• Potential for gravity-fed irrigation systems | • Limited yield and supply capacity<br>• High capital investment costs<br>• Limited irrigable area<br>• Low cost-efficiency for water tanks<br>• Must be communally owned and managed<br>• Isolated systems: No natural recharge and integrated restoration potential at the watershed level | • Link with small earth dams for off-season micro-/ small-scale irrigation<br>• Access to community-based financing mechanisms supported by business activities<br>• Link with national/ international multi-year funding programs<br>• Adoption of low-cost drip and other improved irrigation systems |

*Source* De Trincheria et al. (2017)

## 6.3 Cost-Efficiency

Table 6 shows an estimation of the capital investment costs of best practices on the use of rainwater for off-season small-scale irrigation in arid and semi-arid areas. Community-based RWHI systems present higher cost-efficiency values than the household-based RWHI systems, except for the rock catchment with two ferro-cement tanks of 90 m$^3$. In fact, this system presents the lowest cost-efficiency (104 USD/m$^3$ of irrigated water). Subsurface dams made of soil present the highest cost-efficiency among all RWHI systems (3 USD/m$^3$ of irrigated water).

**Table 5** Specific impacts of different technologies to collect and store rainwater for off-season small-scale irrigation

| | On-farm ponds | Roof catchments | Alluvial shallow groundwater in seasonal sandy streams | Groundwater dams in seasonal sandy streams | Small earth dams | Rock catchments |
|---|---|---|---|---|---|---|
| Specific impact | Household-based | | Community-based | | | |
| Rainfed agriculture | ++ | +/− | +++ | +++ | ++ | +/- |
| Off-season irrigation | +++ | +++ | +++ | +++ | +++ | +++ |
| Supplementary irrigation | ++ | +/− | +++ | +++ | +++ | +/− |
| Kitchen gardening | +++ | +++ | ++ | ++ | ++ | +++ |
| Reduced risk of production failure | ++ | +/− | +++ | +++ | +++ | +/− |
| Improving crop and tree production | +++ | +++ | +++ | +++ | +++ | +++ |
| Improving fodder production | +/− | +/− | ++ | ++ | ++ | +/− |
| Improving wood/fibre production | +/− | +/− | ++ | ++ | ++ | +/− |
| Livestock production | ++ | + | +++ | +++ | +++ | + |
| Nutrition and health | +++ | +++ | +++ | +++ | +++ | +++ |
| Groundwater recharge | ++ | +/− | +++ | +++ | ++ | +/− |
| Maintaining and improving food security | +++ | +++ | +++ | +++ | +++ | +++ |
| Reducing rural poverty | +++ | +++ | +++ | +++ | +++ | +++ |

(continued)

**Table 5** (continued)

| | On-farm ponds | Roof catchments | Alluvial shallow groundwater in seasonal sandy streams | Groundwater dams in seasonal sandy streams | Small earth dams | Rock catchments |
|---|---|---|---|---|---|---|
| Creating rural employment | +++ | + | +++ | +++ | +++ | + |
| Supporting gender equity | +++ | +++ | +++ | +++ | +++ | +++ |
| Improving water productivity | +++ | +++ | +++ | +++ | +++ | +++ |
| Climate change adaptation | +++ | +++ | +++ | +++ | +++ | +++ |
| Resilience to extreme dry conditions | +/− | +/− | +++ | +++ | +/− | + |
| Resilience to variable rainfall | + | ++ | +++ | +++ | ++ | ++ |
| Resilience to extreme rains | ++ | +++ | +++ | ++ | + | ++ |
| Resilience to rising temperatures and evaporation rates | + | +++ | +++ | +++ | + | +++ |

*Importance* High (+++), Medium (++), Low (+), Neutral (+/−)
*Source* De Trincheria et al. (2017)

**Table 6** Estimation of the capital investment costs of best practices on off-season rainwater harvesting irrigation management

| Collection and storage of rainwater | Costs (USD) | Water pumping system | Costs (USD) | Water application system | Costs (USD) | Total costs (USD) | Total cost-efficiency of the capital investment (USD/$m^3$ irrigated) |
|---|---|---|---|---|---|---|---|
| *Household-based systems up to <1 ha irrigation, i.e. kitchen gardening and micro-irrigation* | | | | | | | |
| Upgraded on-farm ponds 50 $m^3$ | 1000 | KickStart Super MoneyMaker pump (SMP) | 100 | LHLCD | 200 | 1300 | 26.0 |
| Upgraded on-farm ponds 100 $m^3$ | 2000 | KickStart Super MoneyMaker pump (SMP) | 100 | LHLCD | 200 | 2300 | 23.0 |
| Upgraded on-farm ponds 100 $m^3$ | 2000 | Sunlight pump | 1100 | LHLCD | 200 | 3300 | 33.0 |
| Roof catchment + ferro-cement tank 56 $m^3$ | 1500 | KickStart Super MoneyMaker Pump (SMP) | 100 | LHLCD | 200 | 1800 | 32.2 |
| Roof catchment + ferro-cement tank 56 $m^3$ | 1500 | Sunlight pump | 1100 | LHLCD | 200 | 2800 | 50.0 |
| Roof catchment + on-farm pond 100 $m^3$ | 2100 | KickStart Super MoneyMaker Pump (SMP) | 100 | LHLCD | 200 | 2400 | 24.0 |
| *Community-based systems up to 1–2 ha irrigation, i.e. micro-irrigation and small-scale irrigation* | | | | | | | |
| Hillside circular earth dam with 800 $m^3$ | 3055 | Diesel/petrol/kerosene pumps | 100 | LHLCD | 1000 | 4155 | 5.2 |
| Rock catchment + 2 ferro-cement tanks of 90 $m^3$ (total volume) | 8240 | Diesel/petrol/kerosene pumps | 100 | LHLCD | 1000 | 9340 | 103.7 |
| Rock catchment + rock dam of 400 $m^3$ | 4000 | Diesel/petrol/kerosene pumps | 100 | LHLCD | 1000 | 5100 | 13.0 |
| Rock catchment + earth dam of 400 $m^3$ | 2000 | Diesel/petrol/kerosene pumps | 100 | LHLCD | 1000 | 3100 | 7.8 |

(continued)

**Table 6** (continued)

| Collection and storage of rainwater | Costs (USD) | Water pumping system | Costs (USD) | Water application system | Costs (USD) | Total costs (USD) | Total cost-efficiency of the capital investment (USD/$m^3$ irrigated) |
|---|---|---|---|---|---|---|---|
| Natural alluvial shallow groundwater seasonal sandy stream with 1000 $m^3$ | 1 | Dabane sand abstraction systems with two dipping wells | 2800 | LHLCD | 1000 | 3801 | 3.8 |
| Subsurface dam made of soil with 2000 $m^3$ | 1800 | Dabane sand abstraction systems with two dipping wells | 2800 | LHLCD | 1000 | 5600 | 2.8 |
| Reinforced rubble stone masonry sand storage dam with 4000 $m^3$ | 15000 | Dabane sand abstraction systems with two dipping wells | 2800 | LHLCD | 1000 | 18800 | 4.7 |

*Source* De Trincheria et al. (2017)

## 7 Conclusions

RWHI management is a subset of rainwater harvesting technologies and practices that allow concentrating and storing rainwater to be used for off-season small-scale irrigation of high-value crops in arid and semi-arid areas. Thus, off-season RWHI management is specifically meant to conduct off-season small-scale agricultural activities, especially kitchen gardens, trees and high-value horticultural crops along riverbanks.

Community-based RWHI systems present higher cost-efficiency values than the household-based RWHI systems. However, the success of any system to use rainwater for off-season small-scale irrigation depends on multivariate factors, among them, multi-dimensional physical and hydrogeological suitability factors coupled with the cost-efficiency and specific technical considerations of the technologies and practices. In addition, the technical and financial capability of the beneficiaries coupled with the revenue potential of the RWHI systems plays a crucial role in the replication of RWHI technologies.

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# Fostering Food Security and Climate Resilience Through Integrated Landscape Restoration Practices and Rainwater Harvesting/Management in Arid and Semi-arid Areas of Ethiopia

**Kifle Woldearegay, Lulseged Tamene, Kindu Mekonnen, Fred Kizito and Deborah Bossio**

**Abstract** Land degradation and rainfall variability are severe problems affecting sub-Saharan Africa. Ethiopia is one of the countries in the region which is hugely impacted by these processes. To circumvent the impacts of these problems, the country has been involved in implementing various landscape restoration and water harvesting (LRWH) practices since the 1970s. However, the success of these efforts has been limited especially at the earlier periods. The major reasons include the top-down approach followed to implementation of the LRWH practices, mismatch between landscape characteristics and recommended LRWH options, lack of appropriate monitoring and maintenance of schemes, and low adoption rate by communities due to limited economic return from the interventions. Despite these bottlenecks, however, various achievements have been recorded in some parts of the country. In those areas, the interventions have significantly changed the environmental and socio-economic conditions of the areas. Understanding the key drivers that promoted successful restoration of landscapes and water resources could help in designing appropriate technologies and their implementation mechanisms. This study aims to assess the biophysical and socio-economic conditions that need to be fulfilled for LRWH technologies to be adopted and be effective and to enhance resilience to climate/rainfall variability. We critically reviewed five successful cases in Tigray region to understand the critical elements to be considered when identifying, introducing and managing LRWH options. The results show that promotion of integrated management practices considering the whole landscape continuum is essential for LRWH options to succeed and create resi-

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lience to climate variability. It is also observed that interventions should be designed considering both agro-ecological, land use/cover, soil, geomorphological, hydrogeological, socio-economic and institutional conditions of specific landscapes/watersheds.

**Keywords** Land degradation · Landscape continuum · Adoption drivers

## 1 Introduction

Many countries in Sub-Saharan Africa (SSA) are challenged by land degradation, low water productivity and high rainfall variability which is often associated with climate change. Land degradation in SSA is affecting 20–50% of the land and some 200 million people (Nkonya et al. 2008; Obalum et al. 2012). An estimated 65% of Africa's agricultural land is degraded due to erosion and/or chemical and physical damage (FAO 2005; UNEP 2008; Vlek et al. 2008). Soil erosion rate in the highlands of Ethiopia reaches over 130 ton $ha^{-1}$ $year^{-1}$ (Berry 2003). Erosion has also caused sedimentation of hydropower dams resulting in significant economic loss due to frequent power cut (Tamene et al. 2011). Climate change also remains a major challenge in Ethiopia. In the year 2015, for example, some part of the country was affected by El-Niño which caused droughts affecting about 10 million people (EMoANR 2015).

In order to enhance food security and conserve the environment, various land and water management interventions have been implemented in Ethiopia. In the years 1976–1985, about 600,000 km of soil and stone bunds and 500,000 km of hillside terraces were constructed, 500 million tree seedlings were planted, and 80,000 ha were set aside for natural regeneration (Berry 2003). After the 1984–85 drought, the massive reafforestation and conservation campaign intensified and until 1990 it is believed that more than one million km of soil and stone bunds and almost one-half million km of hillside terrace were built (Hoben 1995). In addition, more than 80,000 ha of hillside were closed to allow native plant regeneration, and 300,000 ha of trees were planted (Stahl 1990). Currently, the government claims that billions of trees have been planted, and millions of ha of land conserved through the construction of terraces, deep trenches, percolation ponds, etc., across the different parts of the country. In addition, the country has pledged to restore about 15 million ha of land by 2020 as part of the Bonn challenge (WRI 2015).

Despite few and isolated evidences of success stories (e.g. Descheemaeker et al. 2006; Mekuria et al. 2011), most reports and studies claim that the majority of the restoration and water harvesting efforts conducted before mid-1990s were less successful (e.g. Bishaw 2001). Various authors (e.g. Hunting 1976; Stocking 1992; Bishaw 2001) have indicated the reasons for the limited success of the earlier interventions to be both technical and institutional factors. The initial stage of implementation had technical failures such as incorrect spacing and alignment of terraces, poorly organized nurseries and wrong choices of species (Hunting 1976). Stocking (1992) indicated that the pre-1980 period was largely dominated by a "technical-fix" approach, where a physical problem was identified and a physical solution prescribed. The top-down approach followed during identification and implementation of soil and water conservation practices has also contributed to the limited adoption of the technologies and largely to community failure to protect and manage the options (Hunting 1976; Bishaw 2001).

In spite of the observed failures in the 1970s and 1980s, remarkable achievements were made in the last decade. For example, the recent landscape restoration efforts in Tigray, northern Ethiopia, have been labelled as the most successful and recommended to be taken as exemplary for SSA and beyond (Tuinhof et al. 2012). In addition, different types of water harvesting structures (dam, river diversions, ponds, shallow groundwater wells, etc.) have been constructed, and small-scale irrigation is promoted in the region over the last years. The techniques and approaches/processes used for such successful landscape restoration and water harvesting (LRWH) could facilitate technology out-scaling to other areas with similar environmental conditions. This chapter presents the approaches and techniques of LRWH implemented, the multidimensional benefits achieved and the key lessons learned from the implementation of the various interventions in Tigray, northern Ethiopia.

## 2 Characteristics of Tigray Region and Study Approach

### *2.1 Characteristics of Tigray Region*

Tigray region, located in northern Ethiopia, has a population of about 5 million and is characterized by high rainfall and topographical variability. The landform includes highlands (in the range of 2300–3200 masl), moderate relief hills (1500–2200 masl), lowland plains (with an altitude range of <500–1500 masl) and mountain peaks (as high as 3935 masl). According to ENMA (2014), the rainfall in the region dominantly varies from 500 to 800 mm with limited parts of the region mainly the western part reaching up to 1200 mm. The main rainy season is in the months of June to September. The average annual temperature of the Tigray region varies from 10 to 25 °C (ENMSA 2014).

In terms of geohydrology, the region is dominated by rocks/soils with variable hydraulic properties (Woldearegay and Van Steenbergen 2015): (a) the cliffs/steep slopes are mostly rocks which act as recharge areas, (b) the intermediate slopes are dominated by soils/weathered rock of variable hydraulic properties which dominantly range from medium to high and (c) the flat valley floors are mostly dominated by soils and act as discharge areas, depending on the hydraulic behaviours of the soils; these areas are sources of shallow groundwater.

## 2.2 *Study Approach*

This study involved both qualitative and quantitative approaches which include (a) review of technical reports, published articles, annual government performance reports and regional/federal governments' strategy documents, (b) field survey and participatory evaluation of the various sites in order to assess the current status in comparison with previous conditions, (c) groundwater monitoring (water level and quality) before and after the interventions in order to assess the effectiveness of the interventions for groundwater recharge, (d) assessment of the institutional arrangements and governance aspects of the implementation of the LRWH interventions and (e) discussions with local communities on the multipurpose benefits of the interventions.

Though there are several successful interventions in the region, this study is based on evaluation of five sites. The sites were selected considering availability of hydrogeological evidence as to the changes due to the interventions, and that the sites are well recognized at regional, national and international levels. The sites also represent different agro-ecological zone so that lessons learnt can be out-scaled to other areas. Accordingly, the Abreha Weatsbeha, Sero, Dibdibo, Mariam Shewito and May Demu catchments are selected (Fig. 1).

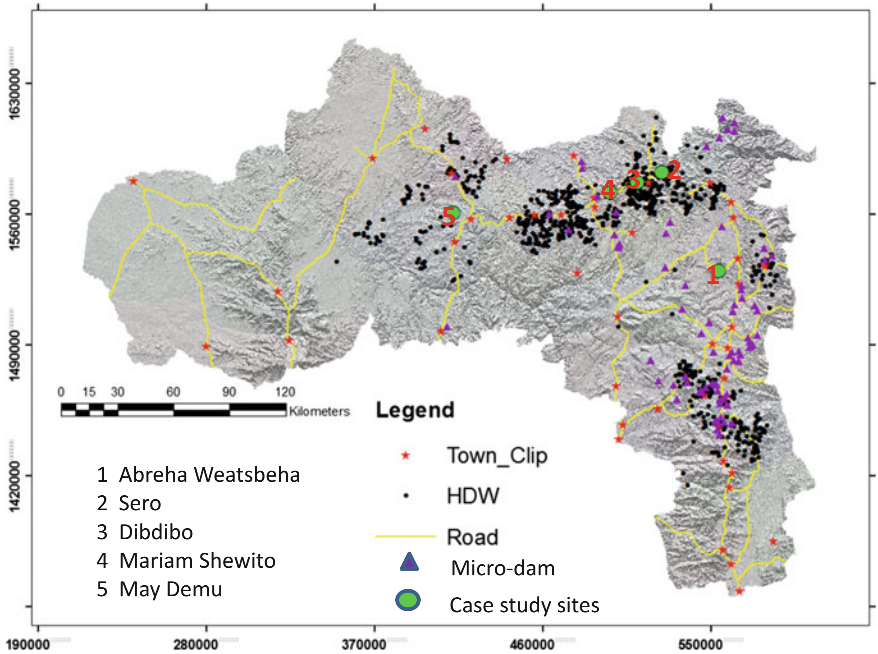



**Fig. 1** Locations of the selected case studies for evaluation of the LRWH practices in Tigray, Ethiopia

## 3 Results and Discussion

### *3.1 Major Trends in Sustainable Land and Water Management in Ethiopia*

Rainfall variability, poor land management, poor soil fertility and soil erosion are serious challenges of food security to rural communities in different parts of Ethiopia. With population pressure and climate change, the severity and impacts of these challenges will likely increase. To improve food security through diversification and intensification at farm scale, improved land and water management are essential. As a result of this, a number of natural resources management efforts have been implemented in Ethiopia since the 1970s. However, most of the introduced technologies were not based on combining scientific and traditional knowledge, and as a result performance was far below expectations. In addition, the top-down approach followed created less incentive and community participation. Recent evidences (e.g. Tuinhof et al. 2012; Adimassu et al. 2016) show that participatory landscape-based integrated natural resources management is useful approach to reduce resources degradation and improve agricultural productivity.

Considering that different potentials and constraints exist across the landscape continuum, it will be essential to design and implement targeted interventions geared to specific landscape and socio-economic conditions. As a result, community-based participatory approaches were used as basis for improving food security through targeted interventions aligned with landscape and socio-economic conditions (e.g. Desta et al. 2005). In line with this, the major LRWH interventions in various parts of the country (especially since 2005) were designed such that (a) deep trenches, percolation pits and afforestation (enclosures, agroforestry) activities at the upper sections of the landscapes, (b) check-dams (gully rehabilitation) and percolation ponds with biological treatments as well as enclosures, agroforestry along the middle sections, (c) gully rehabilitation using a combination of physical (check-dams) and biological measures along the major streams and (d) water harvesting using check-dam ponds, shallow groundwater wells, stream/river diversion and borehole at lower sections of the landscapes were implemented (e.g. Fig. 2).

After around 2005/2006, emphasis was also given to awareness creation, community mobilization, capacity building, partnerships and multidisciplinary approaches to enhance technology adoption and sustainable use. In order to promote adoption, interventions were designed to provide benefits to both upslope and downslope positions of the landscape (because emphasis was given to implement complementary technologies). Below we present examples of successes related to LRWH interventions in the Tigray region.

In all cases, exclosures (especially degraded hillslopes), afforestation (especially deforested uplands/mountains) and grass trips (integrated with terraces) as well as moisture buffering/enhancement techniques were key interventions. In most cases,


**Fig. 2** An overview of implementation of complementary/linked LRWH technologies considering site-specific conditions and the landscape continuum in Tigray, Ethiopia. *Photograph* Kifle Woldearegay

interventions that provide multiple benefits (e.g. grass species that can stabilize bunds, enhance infiltration, fix nitrogen and serve as livestock feed) have also been identified.

## *3.2 Key Impacts of Interventions in the Selected Sites*

### 3.2.1 Impacts of LRWH Practices in the Abreha Weatsbeha Watershed

Before the introduction of integrated LRWH practices, Abreha Weatsbeha site was one of the most degraded, barren lands with no access for water. As a result, the area was designated as less inhabitable, and people were planned to be resettled. Prior to 2005, people were struggling to survive, and over 90% of the people in the Abreha Weatsbeha area were under the Productive Safety Net Programme (TBoARD 2006). However, due to integrated LRWH interventions, the area has become one of the most successful sites in terms of landscape restoration in the world (e.g. Tuinhof et al. 2012).

Different LRWH techniques have been implemented along the landscape continuum that match with the characteristics of the landscape. For instance, the upper section of the landscape which is dominated by fractured sandstone with higher permeability is treated with deep trenches, percolation pits, afforestation and area closures. The middle section which is dominated by weathered sandstone and debris/colluvial materials with relatively higher permeability is treated with series of percolation ponds, check-dams, deep trenches with bunds and afforestation (Fig. 3). Finally, the lower section of the landscape which is dominated by soils (silt and sand) and weathered sandstone is designated as a potential area for shallow groundwater development for small-scale irrigation, water supply and livestock watering (Plane 2). The implemented interventions are generally interlinked such that those at the upper section of the landscape enhances infiltration and groundwater recharge to downslope areas and reduces siltation/sedimentation of the middle and lower sections of the landscapes. Similarly, the intervention at the middle section of the landscape provides a number of benefits including enhancing groundwater recharge to lower sections of the slopes and reducing siltation/sedimentation of farmlands in the lower section of the slopes.

Because of the good match between the "landscape context" and the introduced management options, the impacts of the interventions were very significant. Generally, significant improvements were observed in reducing soil erosion from 80 to 100% capturing of floods in series of ponds and dykes, enhancing soil moisture, improving biodiversity through afforestation and area closures and enhancing overall system productivity. For instance, in the Mendae sub-watershed of the Abreha Weatsbeha area (Fig. 3), the total irrigated land has increased from 2.5 ha in the year 1995 to over 110 ha in 2014 (TBoARD 2015).

Despite the high rainfall variability of the area, shallow groundwater has improved (example from dry to water level up to 1.5 m below ground level) in the lower sections of the landscapes (Fig. 5) as a result of the interventions made at the upper and middle sections of the slopes. As compared to the year 1995, the groundwater quality (TDS) has also improved (Fig. 6) as a result of the groundwater replenishment from surface water due to the interventions which act as

**Fig. 3** Panoramic view of the middle section of the landscape in Mendae sub-watered, Abreha Weatsbeha area where percolation ponds/pits, check-dams, deep trenches, afforestation and other landscape restoration works have been made, Tigray, Ethiopia. *Photographs* Kifle Woldearegay

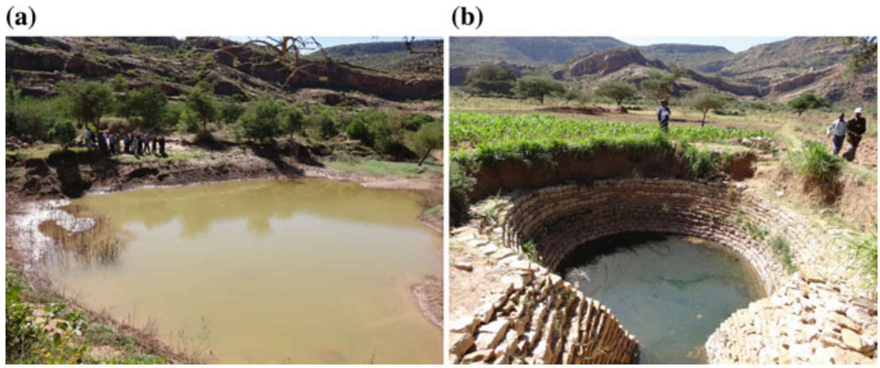



**Fig. 4** Some of the water harvesting technologies in Abreha Weatsbeha, Tigray, Ethiopia: **a** percolation ponds at middle sections of the landscapes acting as groundwater recharge, **b** shallow groundwater wells at lower sections of the landscapes which are used for small-scale irrigation. *Photographs* Kifle Woldearegay

artificial groundwater recharge systems. In the year 2014/2015, over 300 hand-dug shallow groundwater wells have been developed in the lower sections of the slopes and are used for different purposes (small-scale irrigation, water supply and livestock watering) (e.g. Fig. 4). The is impressive because a team of hydrologists who visited the areas in the 1990s for groundwater feasibility failed to access any sign of water up to 30 m depth (EIGS 1995). As a result of implementing proper LRWH and provision of necessary inputs, farmers are able to harvest up to three times a year and increase crop yield from less than 0.24 ton $ha^{-1}$ to over 1.45 ton $ha^{-1}$ (Woldearegay 2013).

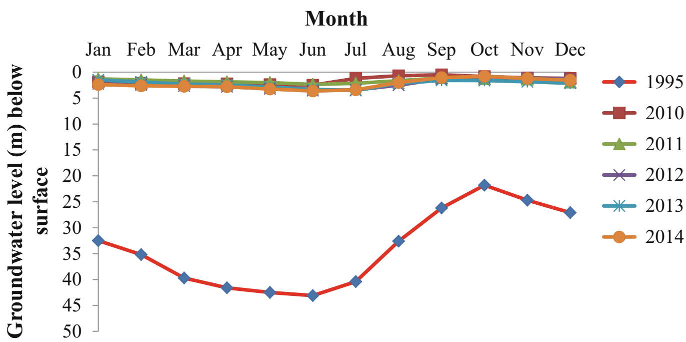
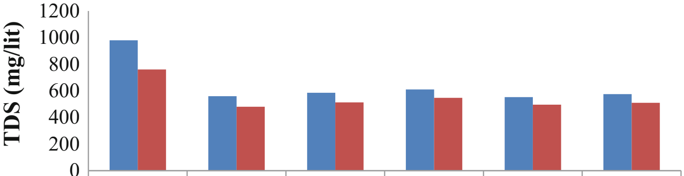



**Fig. 5** Monthly average static groundwater level in Mendae sub-watershed, Abreha Weatsbeha for the years 1995 and 2010–2014




| | 1995 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|
| May | 980 | 560 | 585 | 610 | 553 | 575 |
| Oct | 760 | 480 | 513 | 547 | 496 | 510 |

**Fig. 6** Total dissolved solids (TDS) variation in groundwater in Mendae sub-watershed, Abreha Weatsbeha for the years 1995 and 2010–2014

### 3.2.2 Impacts of LRWH Practices in the Sero Watershed

Similar to that of Abreha Weatsbeha area, the watershed in Sero area was one of the most degraded landscapes with critical shortage of water supply for crop production and livestock watering. As a result, over 70% of the local community were under Productive Safety Net Programme before 2002 (TBoARD 2005). In the year 1995, the total irrigated land in the watershed was only 2.3 ha using water from a spring.

In the last two decades, especially since 2004, different linked LRWH technologies have been implemented along the landscape continuum (e.g. Fig. 7) which include deep trenches with stone bunds, check-dams and percolation pits coupled with afforestation at the upper sections of the landscapes, percolation ponds, check-dams, sediment storage dams, deep trenches with soil/stone bunds and afforestation at the middle sections of the landscapes, as well as water harvesting (using shallow groundwater wells, check-dam ponds, spring development as well as stream/river diversions) and associated irrigation development in the lower sections of the areas.

This effort remarkably changed the watershed whereby over 80% of cultivable land in the watershed is now irrigated. Implementation of appropriate technologies coupled with suitable hydrogeological settings has enhanced groundwater recharge and stream flow. Though there have been changes in rainfall amount over the years, due to the interventions, the groundwater level has improved as compared to that of the 1995 (Fig. 8). Overall, multiple benefits have been recorded as a result of these interventions (Woldearegay 2014): (a) average productivity has increased from 0.38 ton ha$^{-1}$ before 2005 to 1.93 ton ha$^{-1}$ in 2013, (b) irrigation has increased from 2.3 ha before 2005 to 720 ha in 2013, (c) attitude of people has changed: youth have started to be engaged in irrigated agriculture and migration has reduced, (d) regeneration of indigenous trees and improvements in biodiversity in the watersheds.

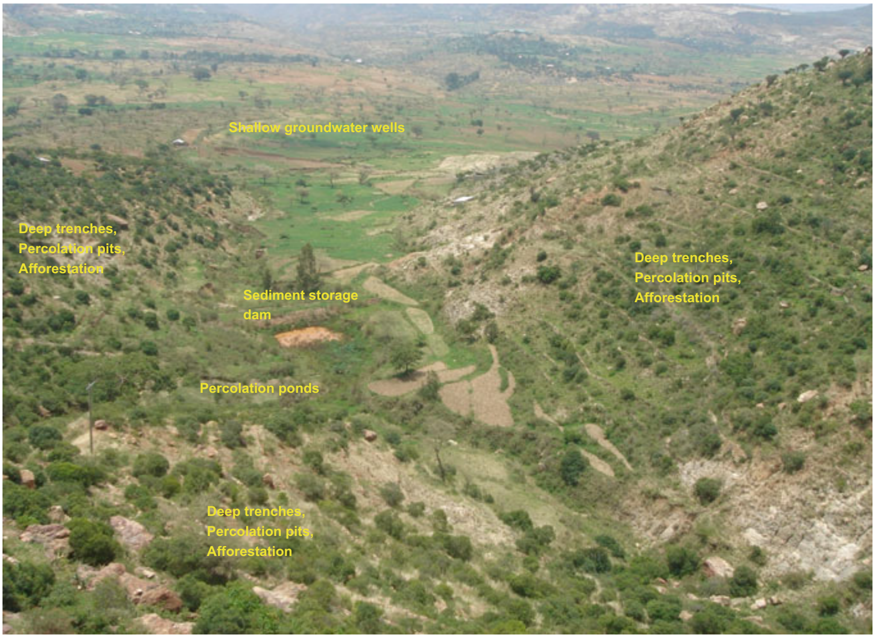



**Fig. 7** View of some of the LRWH technologies implemented in Sero watershed, Tigray, Ethiopia. *Photograph* Kifle Woldearegay

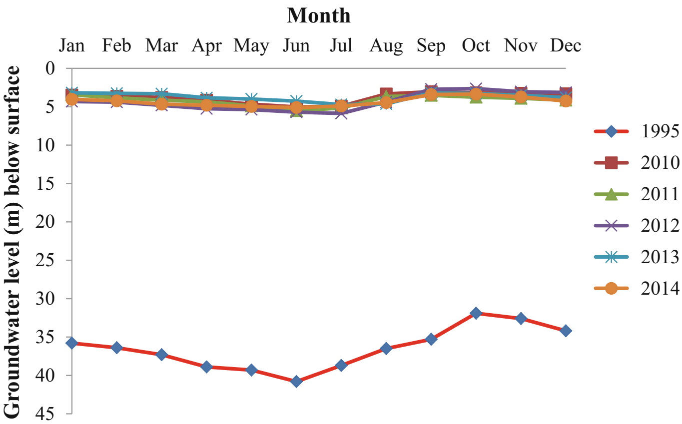



**Fig. 8** Monthly average static groundwater level in Sero watershed, Tigray for the years 1995 and 2010–2014

### 3.2.3 Impacts of LRWH Practices in the Dibdibo Watershed

Similar to the previous watersheds, Dibdibo area has been among the water insecure and drought-prone watersheds, with 90% of the population in the watershed being supported by Productive Safety Net Programme until 2005/2006 (TBoARD 2007). To reverse this, a number of linked LRWH interventions have been implemented since 2004/2005. The key interventions are composed on trenches, percolation pits and afforestation at the steeper and upper sections of the landscapes, check-dams and percolation ponds with biological treatments along the middle sections mainly along streams and check-dam ponds with shallow groundwater wells at lower sections of the landscapes (e.g. Fig. 9). In this watershed, a total of 35 check-dams are constructed at the lower sections of the landscapes and used for surface water storage and groundwater recharge. As a result, irrigation has increased from less than 3 ha in 2004 to over 360 ha in 2014.

### 3.2.4 Impacts of LRWH Practices in the Mariam Shewito Watershed

Mariam Shewito watershed was one of the most drought-prone and food insecure areas with serious gully erosion along major streams until the year 2005. Especially, the main streams were highly dissected by gully erosion: several continuous gullies up to 50 m wide, 20 m deep and over 3 km long have caused major depletion of water and soil in the area, especially until 2005. Since 2005/2006, several initiatives of LRWH such as trenches, percolation pits, check-dams (gully rehabilitation) and percolation ponds with biological treatments, gully rehabilitation using a combination of physical (check-dams) and biological measures along the major streams, and water harvesting using check-dam ponds, and shallow groundwater wells have been implemented in the area. These were implemented considering the landscape

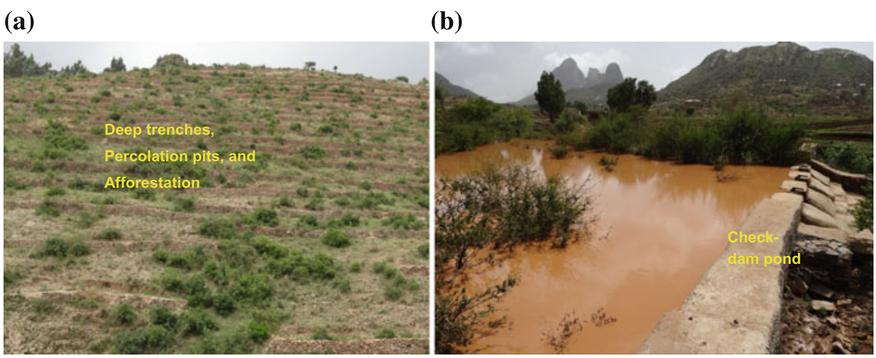



**Fig. 9** Some of the LRWH technologies implemented in Dibdibo watershed, Tigray, Ethiopia: **a** upper part of the landscape and **b** lower part of the landscape. *Photographs* Kifle Woldearegay

continuum (e.g. Fig. 10). Biological measures such as grass strips as well as exclosures and afforestation are also integral parts of the interventions.

A number of benefits have been recorded as a result of these linked LRWH interventions, mainly (a) complete rehabilitation of gullies whereby areas close to treated gullies have become the main sources of water for various purposes, (b) groundwater is enhanced, with rise in static water level from a depth of 28.5 m in 2001 to about 1 m in 2014, (c) irrigation has increased from about 1.5 ha in 1998 to 250 ha in 2014 in which 75% of the cultivable land being irrigated during the dry season (e.g. Figs. 10 and 11).

### 3.2.5 Impacts of LRWH Practices in the May Demu Watershed

The May Demu watershed has been one of the highly degraded areas with little or no conservation practices until 2002/2003. Though the area receives relatively better rainfall (as compared to the previously discussed watersheds), land degradation and associated food insecurity have been a major problem in the area. Over the last two decades, about 150 small- to medium-scale water storage embankment dams have been constructed in Tigray, Ethiopia, mainly for small-scale irrigation purposes (Fig. 12). These dams have been challenged by several problems mainly siltation/sedimentation (Tamene et al. 2006; Berhane et al. 2016) and seepage/leakages (Berhane et al. 2016). With the increase in capacity and awareness, on the multidimensional benefits of combining landscape restoration and water harvesting, dam constructions are being integrated with landscape development.


**Fig. 10** View of LRWH in Mariam Shewito, Tigray, Ethiopia. *Photograph* Kifle Woldearegay

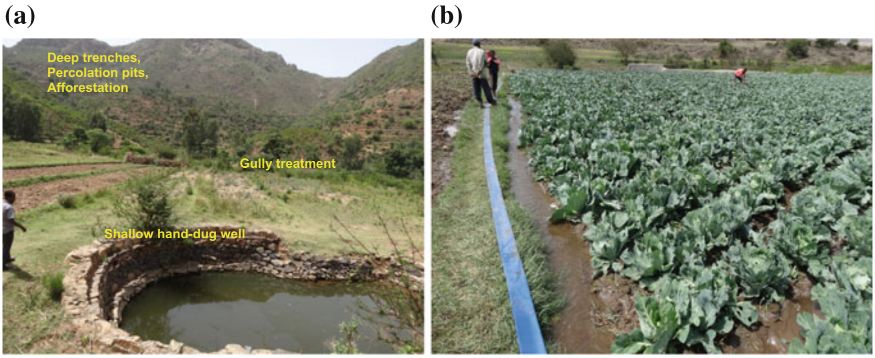



**Fig. 11** Some of the LRWH interventions in Mariam Shewito watershed in Tigray, Ethiopia: **a** shallow groundwater enhanced after the intervention and **b** irrigation development by pumping from hand-dug groundwater wells as well as from check-dam ponds. *Photograph* Kifle Woldearegay


**Fig. 12** Example of upstream landscape restoration, micro-dam construction and irrigation development, the case of May Demu catchment, Shire area, Tigray, Ethiopia. *Photograph* Kifle Woldearegay

Among the many, one typical example with such very successful implementation is the May Demu catchment whereby (Fig. 12): (a) the area upstream of the dam site is treated with deep trenches, percolation pits and afforestation works and (b) downstream of the dam is associated with irrigation development (with surface water from the dam and with shallow groundwater from seepage of the dam). The upstream treatment of the area has reduced siltation of the dam by up to 60% (Woldearegay 2011). Seepage water from the dam has raised the static shallow groundwater level (at downstream of the dam) from a depth of 28 m in 2002 to a depth of about 4 m in 2014 (Fig. 13). The construction of the dam coupled with the presence of pervious weathered rock/soil at downstream of the dam has created a favourable condition for conjunctive use of surface and groundwater at the site.

## 3.3 Key Factors for Successful LRWH in Tigray

Reviewing the 1985–1990 landscape restoration efforts in Ethiopia, Anderson (1998) stated that (a) a restoration programme is unlikely to succeed if it is founded on inadequate information and (b) top-down structure proved to be too inflexible to meet the restoration needs of a large and diverse area, and its single-minded approach lacked the necessary local information to be successful. Small farmers generally were not involved in identifying their needs and problems, establishing priorities, evaluating alternative solutions or planning how they were to be implemented (Hoben 1995). As a result, indigenous farming systems, technical knowledge and common property institutions were ignored, and farmer incentives for participating in community forestry projects were poor (CRDA 1990a, b).

With selected watersheds, as examples, the preceding sections have demonstrated the achievements made in relation to LRWH in Tigray including the hydrological effects and the multidimensional benefits. The main reasons for the achievements observed in the different most successful LRWH interventions are

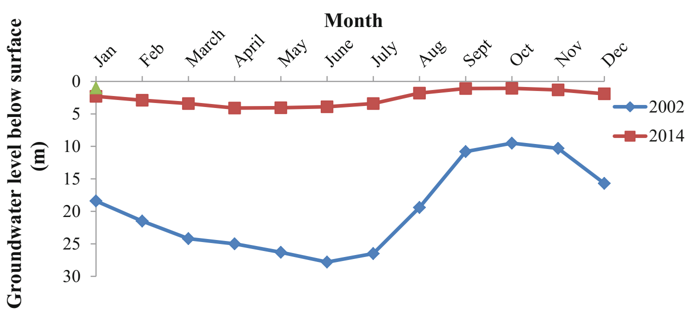



**Fig. 13** Monthly average static groundwater level downstream of May Demu Dam, Tigray, Ethiopia (for the years 2002 and 2014)

due to coordinated efforts in terms of technical, social, institutional/governance and financial aspects.

### 3.3.1 Technical Aspects

Over the years, several LRWH technologies have been implemented in Tigray. Selection of technologies has been almost through trial and errors. In the process, some technologies were found to be more effective than others. For example, stone terraces were the technologies introduced in the 1990s. Because of their less effectiveness in holding moisture and frequent maintenance requirements of these technologies, the adaptation by farmers was not as expected. In addition, these interventions "occupy" cultivated land that competes the small plot size the farmers own in those areas (Adimassu et al. 2014). On the other hand, deep trenches became among the most accepted technologies because of their capacity to reduce erosion and enhance moisture in soil as well to recharge groundwater systems. Because of the shift in focus from soil conservation to water harvesting with application of appropriate linked technologies, and with an approach of maximizing benefits from every intervention, remarkable changes have been recorded in Tigray.

Since the year 2005, the technology, scale and approaches of the interventions have shifted: (a) from trial and error to well-planned and participatory approach, (b) from soil and water conservation to water harvesting, (c) from small-scale to large-scale/landscape level of interventions, (d) from individual/isolated technologies to integrated/linked approach with technologies proven to be effective and climate-smart and (e) from blanket approach to proper technology selection and implementation which considers the hydrogeological setting of the landscapes. Implementation of complementary technologies across the landscape continuum (e.g. Fig. 14) not only benefited users on site but also those downslope and upslope due to generation of multipurpose functions (Scherr et al. 2012). This kind of approach can also facilitate technology out-scaling.

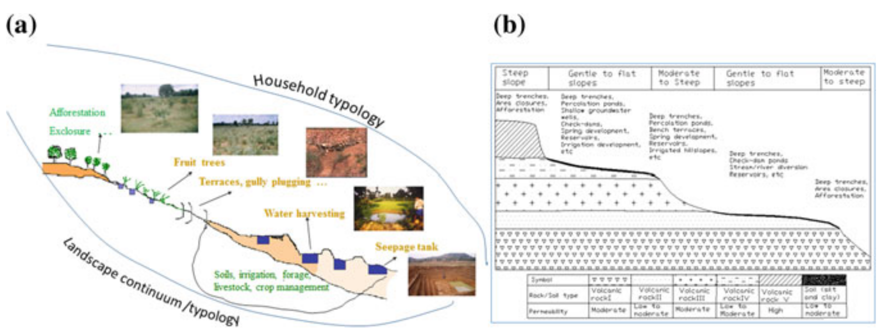



**Fig. 14** **a** Site- and context-specific interventions designed considering household typology and landscape continuum (Desta et al. 2005) and **b** analytical model that can facilitate implementing appropriate land and water management options

In almost all the successful cases, complementary LRWH interventions have been introduced along the landscape continuum whereby (a) deep trenches, percolation pits, check-dams and afforestation activities are implemented at the upper sections of the landscapes which are associated with steeper slopes, (b) percolation pits/ponds, gully rehabilitation check-dams and associated biological measures are done at the middle sections of the landscapes dominated by intermediate slopes, (c) different types of water harvesting like check-dam ponds, spring/river diversions, shallow wells, etc., and associated irrigation developments have been carried out at the lower sections of the landscapes with gentle to flat terrains and (d) in areas where dams have been constructed the conjunctive use of surface and groundwater is being implemented at the lower sections of the landscapes.

Implementation of linked/complementary technologies is found to have multi-dimensional benefits which include the following:

- The construction of deep trenches and percolation pits as well as afforestation activities at the upper sections of the landscapes enhances infiltration of rainwater, reducing sediment transport to downslope areas. This is minimizing siltation/sedimentation of the water harvesting structures at downstream areas and hence enhancing the safety/performance of the interventions.
- The implementation of percolation ponds, gully rehabilitation using check-dams and associated afforestation (biological measures) at the middle section of the landscapes contributes to groundwater recharge, sediment storage, gully bank stabilization and storage of subsurface water. These interventions are enhancing the moisture within the soil along the stabilized streams as opposed to the depletion when gully is developing.
- At the flat/gentle downstream areas, different water harvesting and associated irrigation development practices have been implemented.

With regard to the sequences of the implementation of the interventions, the communities always adopted the "***start from the head principle***" where key interventions were made at the upper section of the landscape to reduce erosion, enhance water infiltration, increase surface cover and overall stabilize the environment.

### 3.3.2 Community Engagement and Mobilizations

The watershed management in Tigray in general has been carried out using two approaches: (a) through free labour whereby a member of the community who has "able body" is required to contribute 20–45 days free labour per year and (b) through Productive Safety Net Programmes (PSNP) which is a labour intensive community-based activity designed to provide employment for chronically food insecure people who have "able-bodied" labour. As reported by the TBoARD (2014), until the end of 2014, over 85% of the landmass of Tigray region is treated with different soil and water conservation interventions.

As witnessed by Tuinhof et al. (2012), the landscape restoration in Tigray has been implemented in a highly organized and participatory manner. The regional state, through the TBoARD, has been giving trainings and support to Woredas. Woredas have been giving trainings and support to Tabias/Kebeles. Tabias/Kebeles (in coordination with Woreda representatives) have been giving training to Sub-catchments where main activity is carried out at this level. Different organizations like farmers unions, women's associations, youth associations, etc., (at all levels) have been fully involved in the mobilization, planning and implementation of SWC activities. The communities have also adopted by-law on how to manage the land after restoration.

Local communities have been getting some awareness on the need for NRM efforts through field demonstrations, experience sharing visits to sites with best practices (including farmer to farmer) and seminars given in local languages. The social learning process has helped to create a demanding society for landscape restoration and water harvesting.

### 3.3.3 Institutional and Governance Issues

The interventions in the Tigray region in general (including the four cases) have been led by two major sectors: TBoARD (Tigray Bureau of Agriculture and Rural Development) and TBoWR (Tigray Bureau of Water Resources) supported by different NGOs and financing organizations. The TBoARD has been leading the watershed movement which includes the constructions of deep trenches, percolation pits/ponds, gully rehabilitation (using check-dams) and afforestation activities. The TBoWR has been leading the development of water resources mainly the study, design and construction of water harvesting schemes (diversion weirs, check-dam ponds, groundwater wells) as well as irrigation infrastructures (canals). This integration among sectors has helped for local communities to benefit from all the interventions at different levels along the landscape continuum: from erosion control and afforestation at upper watersheds to irrigation development and productivity enhancement at farm levels.

The technologies and approaches implemented/adopted were designed in such a way that they work in the local text and should address the priorities of the local communities/users. These have been done through full involvement and capacity building of the communities including experience sharing visits, field demonstration and formal/informal trainings.

In the early phases of landscape restoration in Tigray, farmers were not able to get immediate benefits because of the isolated technologies where the focus was to conserve the environment. To ensure the sustainability, the technologies and approaches implemented have become integrated and with an objective of maximum benefits while conserving the environment. In all the successful sites, water harvesting, irrigation development and hence enhancement of productivity was given due priority in addition to conservation of the environment. The major inceptive of the communities has been the benefit obtained from the interventions in terms of income.

## 4 Conclusion and Recommendations

The approaches and linked technologies implemented in Tigray have proven to be effective in one of the most degraded and drought-prone areas in Ethiopia. Different types of technologies have been implemented at different levels of the landscapes: one technology enhancing the effectiveness and sustainability of the other one. This approach and selection of appropriate technologies has led to the dramatic improvements in water and land management and irrigation development in the region.

Results of the study revealed that upstream integrated landscape level of interventions have resulted in (a) increase in infiltration of rainwater as well as increase in discharge of springs and streams at lower parts of the catchments, (b) raise in groundwater levels from dry states up to 1 m below surface and (c) increase in quality of groundwater due to recharge from rainwater. A systematic and integrated landscape level of intervention has resulted in valley floors which are of high potential areas for shallow groundwater development and an opportunity for the conjunctive use of surface and groundwater.

Despite the high rainfall variability over the last years, through climate-smart landscape restorations and introduction of appropriate water harvesting and moisture conservation technologies it was possible to increase availability of water, enhance productivity of rainfed agriculture as well as irrigated agriculture, and avoid climate related disasters in the studied sites in Tigray region, Ethiopia. Taking into account the local context (soil, geohydrology, climate and socio-economic/political), the best practices in Tigray could be up-scaled to other parts of Ethiopia.

For further out/up-scaling to other parts of Ethiopia and beyond, the following key lessons need to be learned from the experiences of implementing landscape level LRWH interventions in Tigray:

(a) **Learning through processes and by doing**: most of the technologies implemented in Tigray were not through rigorous research but mainly through trial and error, especially at early phases of the introduction of landscape restoration. But at later stages, the technologies and approaches were systematically evaluated, and best practices were implemented in the consecutive years. The approach has been learning from failures and by doing rather than waiting for experimental-based research outputs on best technologies and approaches. This has led to the status where several LRWH technology options were introduced in Tigray region; the region has become LRWH field laboratory.

(b) **Benefit-oriented interventions**: all the interventions were designed in such a way that the technologies and approaches to be implemented at different levels of the landscapes have multiple benefits which range from short-term to long-term. For example, physical gully rehabilitation was integrated with biological measures in order to provide feed for livestock and at the same time increase the effectiveness and sustainability of the physical measures.

(c) **Landscape level of intervention with linked technologies**: at early stages of the implementation of the interventions in Tigray, different technologies were used to be applied without due considerations on the linkages at watershed/landscape level. Through time, however, the approaches of landscape level and integrated approach with appropriate and linked/complementary technologies were designed and implemented. A certain technology implemented at upper part of the landscape has a positive effect to the performance and sustainability of the technologies at the middle sections of the slopes. Similarly, the interventions at the middle sections of the landscapes have positive effect to the performance/sustainability of the technologies implemented at lower sections of the landscapes. This approach takes into account upstream-downstream issues which could emerge as a result of implementing interventions at landscape level.

(d) **Technology selection**: the technologies implemented in Tigray, northern Ethiopia, were redesigned to fit into the local conditions which include the climate (rainfall.), the hydrogeological characteristics of the watersheds and other sociocultural/economic aspects of the areas.

(e) **Leadership and political commitment**: implementation of linked and appropriate technologies at landscape level requires a very strong local leadership, high political commitment and appropriate institutional set-up. These factors, especially the local leadership has played a critical role in the effective implementation of landscape levels of interventions in Tigray, Ethiopia.

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# Towards Optimizing the Performance and Cost-Effectiveness of Farm Pond Technology for Small-Scale Irrigation in Semi-arid Farming Systems

**Stephen N. Ngigi**

**Abstract** Smallholder farming systems in the vast dry lands—semi-humid to semi-arid environments—have been trying different technologies to address frequent water scarcity that affects crop production, and their livelihoods. Climate change has aggravated water scarcity and hence the need for cost-effective adaptation strategies to improve food security. One of the promising technologies is farm pond system that harvest run-off for horticulture production under small-scale irrigation. Therefore, this paper presents the genesis of upgrading the farm ponds by reducing water losses, which builds on the farmers' experiences, through research, development, piloting and scaling up, and integration of other components to develop a technological package that addresses the challenges of horticultural production by smallholder farmers in the dry lands. The technological package which includes tailor-made sizes of farm ponds, low-head drip irrigation systems, and low-cost metallic greenhouses is based on seeking local solutions to local problems by building on farmers' experiences and existing hi-tech innovations that are out of reach of poor farmers. In addition, the socio-economic impacts of the technological package on the livelihoods of smallholder farmers in different parts of the country are highlighted. The technology is scalable and applicable in other countries in Sub-Saharan Africa with similar climatic conditions, farming systems, and climate change challenges that affect the livelihoods of vulnerable smallholder farming communities—periodic water scarcity, inadequate storage and poor water management. However, there is need for improved access to extension and financial services to enhance technology adoption due to its cost-effectiveness and adaptability to different farming systems.

**Keywords** Rainwater management · Drip irrigation · Climate change
Dry lands

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## 1 Introduction

Livelihoods of most rural communities in arid and semi-arid areas, especially smallholder farming systems, are frequently disrupted by persistent droughts and related famine. This is due to erratic climatic conditions characterized by low and unpredictable rainfall and vulnerability to climate change. Inadequate and unreliable rainfall leads to water scarcity, low food production, food insecurity, malnutrition among children, low household income, and environmental degradation, which aggravate poverty and vulnerability among smallholder farmers. The effects of climate change (e.g. irregular rainfall patterns, severe drought, and floods) are already being felt, and most smallholder subsistence farmers who rely on rainfed agriculture are most vulnerable. Climate change is increasing the frequency of droughts leading to water stress, crop failures, and a cyclical reliance on food relief.

The challenge for development agencies is to identify appropriate cost-effective technologies that would help smallholder farmers adapt to climate change and upgrade rainfed agriculture, which is their main source of livelihoods. To address this challenge, there is need for a paradigm shift from ad hoc emergency relief operations to building farmers' resilience and adaptation capacity, especially after the devastating effects of frequent droughts.

Kenya Rainwater Association (KRA) has been seeking for sustainable solutions to address this challenge by promoting integrated rainwater harvesting and management systems for improving agricultural water management by smallholder farmers in the dry lands environment. Research and development of appropriate and cost-effective farm ponds and drip irrigation systems has been going on since 2004, and a prototype has been piloted and tested with encouraging results in terms of water storage, horticultural production, food and nutrition security, and economic empowerment especially for women and youth through agricultural entrepreneurship and rural employment creation.

Farm pond, which is a simple excavated on-farm unlined or lined surface run-off storage reservoir, is one of these adaptation technologies (Ngigi et al. 2005a). Farm ponds come in many shapes and sizes—irregular, circular, or rectangular with vertical or slanted walls depending on soils and various sizes ranging from 50 to 1000 $m^3$ depending on farmer's financial capability and intended water uses (Ngigi 2006). However, the success of farm ponds has been limited by poor performance related to (a) high evaporation and seepage water losses, (b) siltation/sedimentation, (c) health and safety risks, and (d) high investment cost for poor farmers (Ngigi et al. 2012). Figure 1 shows some of these challenges, attempts to address them, and ensuing technological failures of seepage control measures—masonry and plastic lining due to poor workmanship and siltation.

A number of innovations have been tried by various development actors including individual farmers to address some of these challenges in different countries in Sub-Saharan Africa. The paper assesses the evolution of farm pond technology and some of the adaptive innovations that have been developed and tested to improve performance and cost-effectiveness in Kenya. The research is also

**Fig. 1** Some of the challenges related to farm pond technology. *Photographs* Stephen Ngigi

built on past evaluation of some of these innovations in Ethiopia, Kenya, Tanzania, and Uganda (Ngigi 2003) and adapted the findings and lessons learnt in designing an upgraded farm pond that integrates some of these innovations—for reducing seepage and evaporation water losses and improving performance of the farm ponds in terms of water productivity.

Since 2004, KRA has been trying to address the problem of water losses and low water productivity and returns from on-farm storage structures. The long 10 years journey started with an attempt to understand the farmers' challenges; the reasoning behind their efforts to increase on-farm water storage for micro-irrigation; and their motivations to keep on trying despite the ensuing challenges and their limitations. The analysis provided useful lessons, and how to address the challenges without reinventing the wheel, and repeating past mistakes. The assessment focused on the performance of different projects implemented by KRA, which has piloted, replicated, and scaled up the upgraded farm pond technology in different parts of the country. The lessons learnt have been adopted and adapted to further improve the design of the farm pond and implementation approach including innovative financing mechanisms.

The paper aims to promote upgraded farm pond technology that addresses the identified challenges in a cost-effective way and improve the performance in terms of increasing water productivity by reducing water losses, siltation, and wastage. The paper focuses on the farm pond technology, which integrates rainwater harvesting and management as a system. On water management, it integrates both open drip irrigation and greenhouses as complementary technologies that increase water productivity and hence income generation.

The paper is presented in four main sections: (i) introduction which provides the background of the technology development and evaluation; (ii) methodology, which outlines the study area and spatial coverage, research and development process, and agro-hydrological evaluation of farm pond technology; (iii) results and discussions, which highlights adaptive research and development, design of upgraded farm pond, scaling up of upgraded farm pond in Kenya; and (iv) conclusion, which ascertains the importance of adaptive research and development, past efforts, and achievements in the last 10 years in terms of performance and cost-effectiveness of farm pond technology as a climate change adaptation and poverty reduction strategy for smallholder farmers in the dry lands.

## 2 Methodology

The methodology outlines the study area and spatial coverage, research and development process, and agro-hydrological evaluation of farm pond technology. The methodology takes recognizance of the adaptive research and development process undertaken by the author that span over 10 years culminating into an upgraded farm pond technology for arid and semi-arid areas.

### *2.1 Study Area and Spatial Coverage*

The study areas are spread in different countries in Eastern Africa (Ethiopia, Kenya, Tanzania, and Uganda). The selected study areas have similar climatic conditions (semi-humid to semi-arid environment) and farming systems (smallholder-based rainfed subsistence farming). The mean annual rainfall ranges from 600 to 800 mm, but the long-term rainfall analysis shows high spatial and temporal variations ranging from 300 to 1800 mm/year. The mean temperatures range from 28 to 32 °C, and the mean potential evaporation ranges from 1800 to 2400 mm/year. Based on rainfall (P)/potential evaporation ($E_0$) ratio, the study areas fall under agro-climatic zones III–V with $P/E_0$ ratio as follows: 0.50–0.65 (semi-humid); 0.40–0.50 (semi-humid to semi-arid); and 0.25–0.40 (semi-arid) (Sombroek et al. 1980). These are some of the most water-stressed and vulnerable agro-climatic zones where climate change adaptation strategies for smallholder farmers are a priority.

The findings of the regional cases (2001–2003) were complemented by analytical field data in three research sites in Laikipia County over a period of three years (2003–2005). The field research compared water balance i.e. (i) inflows (surface runoff and direct precipitation), and (ii) outflows (losses (seepage and evaporation) and utilization for vegetable production under drip irrigation (Ngigi 2006, 2008). The control was farmers using simple unlined farm ponds, whose performance was compared with lined farm pond of similar size and shape within

**Fig. 2** Monitoring water losses from a lined and unlined farm ponds. *Photographs* Stephen Ngigi

**Fig. 3** Attempts to control seepage (lining with masonry works and plastic). *Photographs* Stephen Ngigi

the same locality). Figure 2 shows water-level monitoring in Matanya—one of the research sites in Laikipia County.

## 2.2 Research and Development Process

The research and development is based on (i) evaluation of past experiences on climate change adaptation strategies in Ethiopia (Kobo, in northern Amhara region), Kenya (Kitui, Laikipia, and Machakos counties), Tanzania (Dodoma region) and Uganda (Mbarara and Rakai districts) (Ngigi 2003), (ii) field analytical research to collect data on water losses and uses in semi-arid Machakos (Barron 2004) and Laikipia Counties of Kenya (Ngigi et al. 2005a, b), and (iii) design, development, and performance evaluation of upgraded farm ponds in semi-arid parts of Kiambu, Kitui, Laikipia, Machakos, Makueni, and Nyandarua (Ngigi et al. 2012, 2014, 2015). The design thus integrated lessons from past experiences to avoid reinventing the wheel and built on farmers' innovations and challenges to make the technology cost-effective and affordable by most smallholder farmers. Figure 3 shows some of the tried innovations for controlling seepage water losses.

## 2.3 Agro-hydrological Evaluation of Farm Pond

The agro-hydrological parameters of the common truncated cone-shaped farm ponds used in the water balance analysis (Eq. 3) are illustrated in Fig. 4 (Ngigi et al. 2005a; Ngigi 2006). The agro-hydrological parameters include both hydrology and crop water requirements (inflows and outflows data). The hydrology data include inflows (precipitation (direct rainfall) and surface run-off) and outflows (evaporation and percolation/seepage). The crop water requirement is an outflow measured using low-head drip irrigation water supply.

To monitor the water balance, the dimensions of the farm pond are a prerequisite. The dimensions include the maximum water depth, top and bottom widths, and the side slope, were measured directly and used to compute the storage capacity, and hence change in volume (Ngigi et al. 2005a; Ngigi 2006). However, the dimensions vary for different designs and shapes of farm pond.

The volume and exposed surface area of the farm pond shown in Fig. 4 are expressed as functions of depth of water by applying solid geometry Eqs. (1 and 2) developed by Helweg and Sharma (1983).

$$V = \frac{1}{3}\pi h\left[3r^2 + 3nhr + n^2h^2\right] \quad (1)$$

$$A = \pi(r + nh)^2 \quad (2)$$

where $V$ = storage capacity of the pond ($m^3$), $A$ = exposed surface area ($m^2$), $h$ = water depth (m), $n$ = side slope$^{-1}$ (Fig. 1), and $r$ = bottom radius of the pond (m).

Equations (1 and 2) and the respective farm pond dimensions were used to determine the on-farm water balance of the RHM system as shown in Eq. (3) where d$V$/d$t$ is the change of volume of stored water over time.

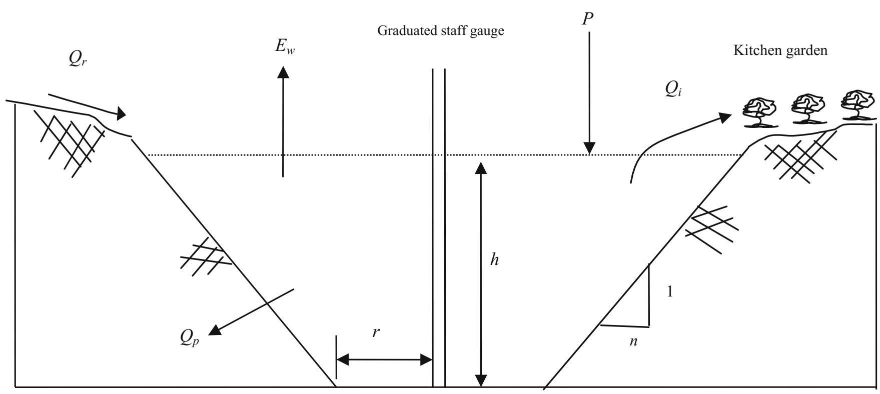


**Fig. 4** Farm pond layout showing agro-hydrological parameters. *Source* Ngigi et al. (2005a)

$$\frac{dV}{dt} = (Q_r + PA) - \left(Q_i - E_w A - Q_p\right). \quad (3)$$

where $V$ = storage of the reservoir ($m^3$), $Q_r$ = surface run-off ($m^3\ s^{-1}$), $P$ = direct precipitation ($m\ s^{-1}$), $Q_i$ = irrigation requirement ($m^3\ s^{-1}$), $E_w$ = open water evaporation ($m\ s^{-1}$), $A$ = exposed surface area ($m^2$), $Q_p$ = seepage losses ($m^3\ s^{-1}$), and $t$ = time (s).

The monitoring of the water levels using a graduated staff gauge, evaporation from the pan, and rainfall from the rain gauge were recorded daily at 9 am and 3 pm. The increase in water level is attributed to run-off and direct rainfall (inflows) and water losses (evaporation and seepage) over the rainfall duration and water usage for irrigation (outflows). Surface run-off was recorded by a pipe sampler, which a non-mechanical run-off measuring device designed on the principle of uniform fluid flow (Hai et al. 2004). It is a rectangular-shaped metallic channel (242 mm wide, 156 mm high, and 465 mm long) made of 2-mm-thick mild steel (Ngigi et al. 2005a). Direct rainfall was measured by a rain gauge, and evaporation by an evaporation pan, which was installed at each research site.

The water levels were converted to volume and exposed surface area, respectively, using depth-volume and depth-surface area relationships in Eqs. (1 and 2). The exposed surface area determines the evaporation losses, while seepage losses depend on wetted surface area and soil characteristics. Seepage losses were computed from the water balance analysis using Eq. (3), in which all the other parameters were measured. Besides, the results were compared with those from lined (no seepage losses) and unlined farm ponds to reduce errors that could be associated with the measurable parameter. Each site had two comparative farm ponds, one lined with plastic sheet to control seepage and the other one unlined for the purpose of verifying the water balance results (Ngigi et al. 2005a; Ngigi 2006).

The amount of water supplied by drip irrigation, i.e. the recommended 2–3 irrigation applications amounting to 40–60 l $day^{-1}$ for a 15 $m^2$ area planted with 100 plants (Ngigi et al. 2000; Ngigi 2002), was compared to the actual daily crop water requirement. A 20-litre bucket kit low-head irrigation system, as shown in Fig. 5, was used. The bucket is filled 2–3 times a day, early in the morning and late afternoon to avoid higher direct evaporation losses. The crop water requirement (water depth) was converted to volume for the irrigated area and compared with the amount of water supplied by the drip irrigation system. The use of drip irrigation to supply supplemental irrigation water requirement during the dry spells was also assessed with respect to the farm pond water storage. Drip technology was considered due to its high efficiency, simplicity, and limited quantity of water in the farm ponds (Ngigi 2008)

Based on the results from the agro-hydrological evaluation, the evolution of the farm pond technology started in 2004, when lining of farm ponds with locally manufactured ultra-violet resistance plastic lining (dam-liners) to reduce seepage was piloted in Ndeiya Karai, Kiambu County. For ease of lining, the truncated

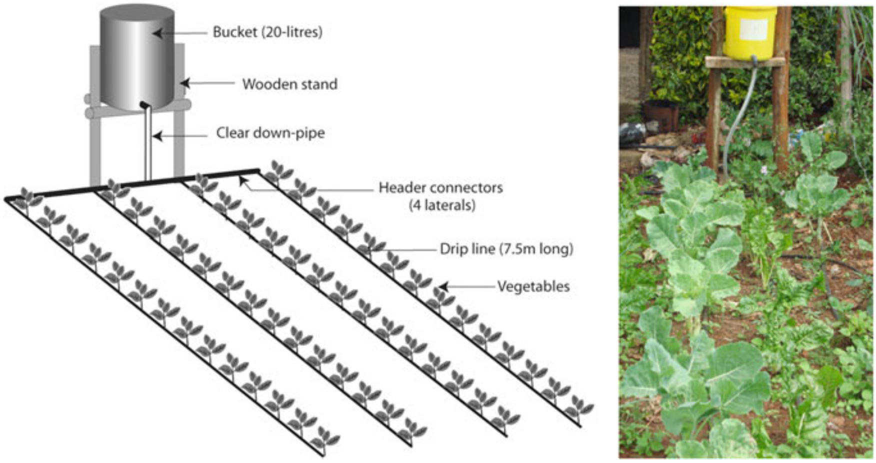


**Fig. 5** Typical 20-litre low-head drip irrigation system mainly used for kitchen garden. *Source* Ngigi et al. (2005a)

rectangular inverted pyramid-shape was adopted instead of the truncated inverted cone-shape. Thus, the upgraded farm pond is an underground run-off storage reservoir—a truncated rectangular inverted pyramid-shaped, which is lined with a 0.8-mm-thick ultra-violet resistant plastic sheet (to control seepage losses), and roofed either with iron-sheet or shade net (to reduce evaporation, contamination and risk of drowning).

## 3 Results and Discussion

The agro-hydrological evaluation of the farm ponds revealed that one of the challenges was how to reduce the seepage and evaporation water losses. High water losses have certainly contributed to the low technology adoption rate and hence low agricultural production (Ngigi et al. 2005b) because of water scarcity related to poor rainfall distribution, drought recurrence, and climate change. Moreover, some farmers had abandoned their farm ponds claiming they were not useful as they only stored water for short periods after the rains, which was not enough to bridge even the intra-seasonal dry spells when the crops require additional water (Ngigi 2003).

### *3.1 Quantification of Water Losses*

The quantification of water losses is important to determine if control measures are appropriate or cost-effective and if any trade-off is necessary. Seepage and evaporation losses were found to vary from one farm pond to another due to size and side slopes of the farm ponds and spatial variation in soil characteristics (Ngigi et al. 2005a). The spatial soil characteristics explain why even farm ponds on the same farm showed different results. The relationship between water losses and water depth in the farm pond fitted well on a power function due to their truncated cone-shapes and hence the higher the water level the higher the seepage losses (Ngigi et al. 2005a).

Thus, the relationship between water depth and water losses (seepage and evaporation) shows that water losses increase with water depths and exposed surface area (Ngigi et al. 2005a). The evaporation and seepage losses ranged between 0.1–0.3 $m^3$ $day^{-1}$ and 0.03–0.4 $m^3$ $day^{-1}$, respectively (Thome 2005) and on average accounted for 30–60% of the total harvested water (Ngigi 2006). Evaporation rates in the study area are high ranging from 5 to 8 mm $day^{-1}$, and since the farm ponds are not covered, more water was lost due to evaporation than seepage for farm ponds on clay soils. This shows where emphasis on water loss control measures should be placed—either on evaporation and/or seepage—a trade-off depending on allowable water losses and cost-effectiveness.

However, for farm ponds on sandy soils, where seepage rates are over 2 $m^3$ $day^{-1}$, seepage losses are accounted for more than 80% of total water losses and hence most of the water was lost almost immediately after the rains. Here, the priority should be given to seepage control measures. Due to high losses, stored water would not be adequate to meet the crop water requirements either to mitigate intra-seasonal drought or off-season irrigation.

Moreover, water shortage was aggravated by low storage capacity (i.e. 30–50 $m^3$) of most farm ponds (Ngigi 2003). Such low storage capacities are not adequate for full irrigation application, but can be used for supplemental irrigation, either to mitigate intra- and/or off-season dry spells. The poor performances of farm ponds may have led to inadequate maintenance or abandonment and generally low adoption by other farmers. To address these challenges, some innovative farmers had tried several techniques to reduce the seepage without much success. However, ultra-violet resistant plastic lining, often referred to a dam-liner, is one of the promising cost-effective seepage control options that was adopted for upgraded farm pond.

Therefore, water losses can be reduced by lining the farm ponds (for example, with ultra-violet resistant plastic lining) and/or covering the ponds either by roofing with locally available materials or planting non-fruiting passion variety. Seepage rate also depends on textural composition of the underlying soils, method of construction and compaction, life of the farm pond, and maintenance. It was reported in a few cases that seepage losses reduced over time as a result of siltation, which seemed to seal the surface of the farm ponds depending on the clay and silt contents of the sediments (Ngigi 2003).

The effect of ultra-violet resistant plastic lining in terms of reducing seepage water losses was encouraging. The lined farm ponds (experimental control) attested to this, as they were able to store water for longer duration (Ngigi et al. 2005b). The results show the benefits associated with controlling water losses and thus improving irrigation water management. Reducing water losses means more water for the crops especially to meet water demands during the dry seasons, which sometimes coincide with critical growth stages. The benefits of reducing water losses were greater in areas with sandy soils (Ngigi 2006). Therefore, lining the farm ponds would improve their performance and enhance their adoption and scaling up. The anticipated results would be improved water storage, crop production, food security, and rural livelihoods.

## 3.2 Adaptive Research and Technology Development

The results of the water losses analysis led to the research-based evolution of the upgraded farm pond technology shown in Fig. 6. The pilot project in 2004 that focused on seepage control with plastic lining encountered some challenges (durability of open dam-lining material, siltation and risk of drowning, and mosquito breeding), which informed the farm pond evolution process.

The durability of the dam-liner was affected by ultra-violet deterioration due to inferior quality whose lifespan was less than assured by the manufacturer and shrinkage (Mbuge 2009). The results were shared with the local plastic manufacturer, who has accordingly improved the quality as evidenced by the durability of installed liners in 2008 which are still functional. The improved design also incorporated a 5% shrinkage allowance in the calculation for the surface area of the dam-liner.

The storage capacity of the farm pond is matched to the seasonal crop water requirement computed from the size of the drip irrigation system to ensure adequate

**Fig. 6** Evolution of water losses (seepage and evaporation) control measures. *Photographs* Stephen Ngigi

water for the entire dry spell or crop growing season (Ngigi et al. 2012). For example, a 50 $m^3$ farm pond goes with a 230-litre mini-tank drip irrigation system, which covers 250–300 $m^2$ of land. The crop water requirement is calculated as follows: 230 l twice a day, hence 460 l $day^{-1}$ that amount to 46 $m^3$ for horticultural crop with a 100-day growing period.

Smallholder farmers in the study areas have been using hand-watering application methods to water their kitchen gardens (Ngigi 2003). However, due to the limited storage capacities and excessive water losses, this application method led to inadequate irrigation water supply and subsequently crop failures. This means the harvested rainwater (run-off) barely met the water requirements, which affected crop growth and yields (Ngigi 2006).

The evaluation of water application rate of the low-head drip irrigation system revealed that the recommended 2–3 buckets (i.e. 40–60 l $day^{-1}$) for an area of 15 $m^2$ was adequate to supply the required amount of water (Ngigi et al. 2000). From a rough estimate of daily crop water requirements using the average evaporation rate of 6.5 mm $day^{-1}$, an irrigation unit of 15 $m^2$ (one bucket kit) will require 0.054 $m^3$ $day^{-1}$ (i.e. 6.5 mm $day^{-1}$ $\times$ 15 $m^2$ $\times$ 0.55). The factor 0.55 indicates the percentage of the soil profile of the cropped area wetted by drip irrigation, which ranges between 0.5 and 0.6 (Gathuma 2000). Therefore, low-head drip irrigation system can adequately meet the daily crop water requirement if matched with the farm pond storage capacity (Ngigi 2008). Lifting water using a hand pump (shown in Fig. 7) complements water management, as it reduces water losses and risks of falling into the farm ponds (Ngigi et al. 2012, 2014).

In addition, locally assembled and improved greenhouses, as shown in Fig. 8, have also been incorporated in the farm pond technology especially for weather-sensitive crops like tomatoes and capsicum. The greenhouses have greatly increased water productivity and horticulture production, and it is amazing that in only one season, a farmer can be able to recover the investment cost of USD 1000 (RHM systems) and USD 1200 for a 120 $m^2$ greenhouse (for locally made structure or USD 2000 for imported metallic structure) from a net seasonal revenue of USD

**Fig. 7** Incorporating drip irrigation technology for horticulture production. *Photographs* Stephen Ngigi

**Fig. 8** Comparison of wooden and metallic greenhouses being adopted. *Photographs* Stephen Ngigi

2000–2500 (Ngigi et al. 2012). It is worthwhile to note that although the locally made wooden structure is cheaper; its durability is short (1–3 years) due to termite infestation and strong winds compared to 5–10 years for the imported metallic greenhouses. Low-cost metallic greenhouses are being developed and piloted by KRA to further reduce the investment cost for smallholder farmers.

However, with open drip irrigation, the seasonal return ranges from USD 250–600 depending on type of crops and hence a cost recovery period of 2–4 seasons (1–2 years). These financial projections are becoming attractive to micro-finance institutions, which have started providing credits to smallholder farmers. This means farm pond can transform smallholder farmers from subsistence to commercial agriculture with linkage to the markets through farmers' cooperatives/marketing associations. Therefore, income generation is the driving force for promoting sustainable and cost-effective innovations for smallholder farmers (Ngigi et al. 2015).

Based on the emerging financing mechanisms and promising returns, many smallholder farmers are willing to adopt the technology. Some farmers have also adopted a phased implementation process—a farmer can start with the lining, then roofing later or opt for fencing especially for large farm ponds (>150 $m^3$) depending on cost and source of funding for the investment.

### *3.3 Scaling Up Upgraded Farm Pond in Kenya*

The farm pond harvest and store surface run-off and direct precipitation (either from iron-sheet roof or through the 80% shade net roof) (Ngigi et al. 2012, 2014). For a 50 $m^3$, the top and bottom dimensions are 8 m by 6 m and 4 m by 2 m, respectively, while the depth is 2 m—with 1:1 side slope (Ngigi et al. 2012). Different sizes/dimensions of farm pond can be adopted depending on water demand, for example, 72 or 90 $m^3$ storage capacity, are being promoted for primary schools—vegetable production, establishment of tree seedling nurseries, and supplementary irrigation of tree and fruit seedlings (Ngigi et al. 2012, 2014).

The upgraded farm pond was improved to reduce (i) water losses (seepage and evaporation), (ii) health and safety risks for both human and domestic animals, and (iii) siltation and environmental degradation, and increasing water use efficiency, and economic returns. Thus, the upgraded farm pond is roofed either with iron-sheets or shade nets to (a) reduce the water losses through evaporation, (b) control mosquito breeding, (c) to reduce risk of children and domestic animals drowning, and (d) protect the dam-liner from malicious damage and deterioration from direct exposure to sunlight.

The original farm pond design adopted iron-sheet roofing (first generation), but shade net roofing has been adopted to reduce cost (second generation) and environmental degradation (Ngigi et al. 2012). To avoid risk of drowning for both human and domestic animals, a roofing structure have been incorporated, which has evolved over the years, from timber structure and iron-sheets (first generation of 2007/8), to timber structure with 80% shade net (second generation of 2009/10), to simple metallic structure with shade net (third generation 2011/12) (Ngigi et al. 2014), and recently adoption of flat-net roofing as shown in Fig. 9 (fourth generation) that further reduces the roofing cost for large farm ponds.

To reduce siltation and improve water quality, a double chamber silt trap that was adopted from Ethiopia has been incorporated and fitted with screen filter to prevent floating debris from entering the farm pond. The silt trap consists of a simple masonry double chamber (each of 0.6 m by 0.6 m by 0.6 m) which, allows silt to settles as the water enters into the farm pond. Larger dimensions are adopted for bigger farm ponds. Surface run-off collects a lot of silt especially if the catchment is bare e.g. drainage from roads and foot paths. The silt trap is designed to act both as an inlet of the farm pond as well as the overflow. There are two inlets fitted with 4-inch PVC pipes and screen filters to prevent floating debris from entering the farm pond.

The following are some of the experiences in different semi-arid counties that highlight successes and challenges in scaling up integrated farm pond technology in Kenya.

**Fig. 9** Dome-shaped and flat-net roofing for farm pond. *Photographs* Stephen Ngigi

*Ndeiya Karai in Kiambu County*: Ndeiya Karai is one of the semi-arid parts of Kiambu County, on the leeward of Ngong Hills, bordering Kajiado County, with mean annual rainfall of 600–800 mm year$^{-1}$. It was previously used as grazing land by the neighbouring pastoralist Maasai community. The government settled landless people from the humid areas of the county after independence, but their farming system—borrowed from high rainfall areas—was not suitable for the dry lands environment. Due to persistent crop failure and reliance on relief food, some of the smallholder farmers formed self-help groups with the aim of collectively improving their livelihoods. Some of these farmers' groups approached KRA for support to address their water scarcity challenges; and in 2004 with financial assistance from German Development Service (DED), demonstration of 30 farm ponds—only improved lined with ultra-violet resistance plastic—was done on selected farms. The 50 m$^3$ farm ponds also adopted regular dimensions—shift from truncated cone-shape to truncated pyramid-shape—for ease of lining. The farm ponds performed well at the beginning, but after 1–2 years, their performance deteriorated for a number of reasons: (i) high siltation; (ii) destruction by animals (e.g. dogs tearing the lining on their way out after watering); (iii) shrinkage of the dam-liner due to poor quality and low UV resistance; (iv) high evaporation water losses; (v) low water use efficiency—hand-watering; and (vi) high security and health risks—drowning of children and domestic animals and incidence of malaria breeding. This was our first failure that provided a turning point on our search for a sustainable solution. Ndeiya Karai has recently benefited from the advancement of the technology, where over 70 farmers were targeted for scaling up of the latest design of farm pond including simple hand pump and low-head drip irrigation systems—matched with the size of the farm pond—through a KRA project funded by the African Water Facility of the African Development Bank (AfDB/AWF). Moreover, some of the target farmers also benefited from the County Government, which provided them with greenhouses to increase the productivity and benefits of the farm ponds.

*Promotion of first generation of upgraded farm ponds*: To address the challenges encountered in Ndeiya Karai, deliberate efforts were made to improve the design and performance of the farm ponds. In 2008, the design was improved by (a) roofing with timber structure and iron-sheets to reduce evaporation by 100%, (b) installation of a simple double chamber silt trap, and (c) adoption of 5% shrinkage allowance on the dimensions of the dam-liner (based on research (Mbuge 2009) and integration of complementary technologies, i.e. low-head drip irrigation for vegetable production and simple hand pump (hip pump). This was the first generation of upgraded farm pond that addressed most of the earlier identified challenges. One hundred and thirty (130) of such farm ponds were demonstrated in Laikipia and Nyandarua Counties; 30 each in Rumuruti (Laikipia West), Umande (Laikipia East) and Ndaragwa (Nyandarua North); and 40 in Mashuru (Kajiado East). The farm ponds were successful and most of them are still operational to date, and farmers have reported seasonal income ranging from USD 300–600 with open drip irrigation and USD 1000–2000 with greenhouses. The impact generated a lot of interest with farmers, and development partners, who were, however, sceptical on their adoption due to the high investment cost (USD 2000), which was mainly attributed to the roofing structure. To address this concern, the second generation of farm pond was developed, which replaced the iron-sheet roofing including gutters with shade net roofing—80% shading, which allowed direct precipitation—with lighter wooden structure. The trade-off allowed acceptable evaporation water losses, but reduced the cost by 40% (from USD 2000 to USD 1250). Thirty of these farm ponds were demonstrated in Umande, Laikipia East, and the returns to investment were similar to the previous design. Our attempt to scale up the second generation of farm pond design in Ukambani region led to development of the third generation design. While the conditions were conducive for adoption of the second generation in Laikipia East, due abundance of timber and low termite infestation, this was not the case in Ukambani region. Another drawback was degradation of the wood/timber due to exposure to moisture, which led to low durability of the roofing structure and hence its short life. The third generation was developed after discussions with the Ukambani community on the proposed design. It maintained the 80% shade net but replaced the light wooden structure, with simple metallic structure and further reduced the cost by 50% (to USD 1000 for a 50 $m^3$ farm pond) from the first to the third generation design.

*Promotion of third generation of upgraded farm ponds*: After the successful development and launch of the third generation design of farm pond in Makueni County in 2010, over 600 farm ponds have been constructed in different Counties of Kenya, in particular, 220 in Ukambani region, 100 in Laikipia County and 80 in Kiambu County, 50 in Kajiado County; and 150 for self-funded individual adopters. Some farmers are adapting bigger sizes of farm ponds, and this is made possible since our design is flexible to suit different sizes and farmers preference. For example, a 2-m extension of the 8m $\times$ 6 m top dimensions gives a 72 $m^3$ farm pond (with top dimensions of 10m $\times$ 6 m)—we maintain the top width at 6 m to maintain the span of the roofing structure. All the KRA-initiated scaling up projects promote the integrated package including water management technologies, and more than 80% have been successful and sustainable. Despite the positive economic impacts, the rate scaling up is slower than expected, and we are adopting business approach and linking farmers with micro-finance institutions to enhance the process. However, since the technology has proven cost-effective with high returns, there is need to increase investments to encourage more farmers to adopt and transform their low return rainfed subsistence agriculture to small-scale agro-entrepreneurship. Other development partners have also been adopting our design, while majority others are only promoting plastic lined farm pond of different sizes up to 1000 $m^3$. A number of County Governments in Kenya have also been promoting the farm pond technology, but promotion of the upgraded farm pond is being hampered by the perception that the investment cost is high and beyond the reach of most poor farmers. From past experience, the reduced water losses, security, and health risks increased water productivity—more production per drop of water, and durability/sustainability of the upgraded farm pond (from one to more than ten years), outweighs the extra investment cost (Ngigi et al. 2015). The fourth generation roofing structure for bigger farm ponds is being piloted, and it replaces the metallic structure with flat-net roofing tightened by galvanized wires anchored on sub-surface reinforced concrete metal bars spaced at 1 m along the perimeter. For security risks, the farm pond should be fenced with chain-link and passion fruit planted along the fence as a wind breaker to reduce evaporation.

## 4 Conclusions

The poor performance of farm pond technology has affected the adoption of the technology. Many early lead farmers were disappointed and some abandoned the technology all together. The agro-hydrological evaluation, therefore, focused on improving the technology by reducing water losses and incorporating drip irrigation technology as an efficient water application system. Appropriate innovations were adopted to make the technology cost-effective and affordable by smallholder farmers.

The upgrading of the farm pond technology involved research and development as follows: (a) s*ituational analysis*—learn from farmers' experience and knowledge and roles of different stakeholders; (b) p*roblem diagnosis*—quantify the problem to confirm and demonstrate farmers' challenges and new innovation; (c) provision of *viable and innovative options* to address the problem and adopt the most *cost-effectiveness innovation* that is acceptable to the farmers to enhance adoption; (d) i*nvention*: do not *reinvent the wheel*—build from farmers' and past experiences and blend with modern technology; and (e) p*iloting and demonstration*: technology promotion should *demonstrate* how the *technology works and its impacts*—real-life experience with supporting data to verify the performance and outcome—seasonal income generated from different horticultural crops and water management—open drip irrigation or greenhouses.

The innovation addressed (a) technologies for rainwater harvesting and storage (farm pond) and management and utilization (drip irrigation and greenhouses, (b) viable financing mechanism due to its cost-effectiveness, which is attractive to financial institutions, (c) adoption of phased implementation—stages of farm pond construction and complementary technologies, and (d) sustainability aspects both health and environmental related—controlled mosquito breeding and replacement of timber for construction to avoid deforestation.

The second and third generation of the upgraded farm pond is cost-effective, as the shade net roofing is about 50% cheaper than iron-sheets due to low unit cost (per $m^2$) and lighter roofing structure. However, due to environmental concern and termites attack on wooden roofing structures, a simple dome-shaped metallic roofing structure was designed for shade net roofs, which has further reduced the cost of roofing to about 40% of the total cost (to USD 1000) for a 50 $m^3$ farm pond. Moreover, for bigger farm ponds, flat-net roofing suspended by a network of galvanized wires has been adopted, which further reduces the cost. The shade net roofed farm ponds have also been adopted for fish farming by some innovative farmers, and the results are encouraging—enhancing multiple uses. Therefore, the evolution of roofing structure has drastically reduced the cost of the farm pond by up to 100%—from USD 2000 to USD 1000 for a 50 $m^3$ farm pond. Roofing has also controlled mosquito breeding and allowed some farmers to incorporate fish farming. The risk of human drowning was also reduced by incorporating a simple hand pump (hip pump from KickStart International), which ease lifting of water from the farm pond into the low-head drip irrigation system.

The desired results and impacts from adopting farm pond are climate change mitigation and adaptation, food and nutrition security, improved livelihoods through better land and water productivity leading to agro-entrepreneurship, and poverty reduction in the dry lands. It is envisaged that these impacts would lead to technology adoption, adaptation, and increased investments for scaling up, which would be enhanced by development of an integrated business plan and cost-effective financing mechanisms for smallholder farmers. The farm pond technology is simple and can be easily implemented by farmers with minimal technical assistance.

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# The Promise of Flood-Based Farming Systems in Arid and Semi-arid Areas

**Matthijs Kool, Frank van Steenbergen, Abraham Mehari Haile, Yasir Mohamed Abbas and Eyasu Hagos**

**Abstract** Flood-based farming systems (FBFS) are extensively used throughout Sub-Saharan Africa. Consisting of spate irrigation, flood recession and flood rise farming, inundation canals and depression agriculture, it is estimated that these farming systems cover close to 25 million hectares in this region alone. For each of these FBFS, different techniques and approaches can be used to develop their potential. A wide variety of best practices can be captured from around the world that are instrumental to strengthen FBFS. Significant gains can be made in the area of water distribution, field water management, groundwater use, agronomic practices, multi-functional use of floodplains as well as their governance. Thus, this chapter discusses the effect of FBFS on sedimentation processes and soil fertility, the link between the distribution and management of both floodwater and run-off and the different ecosystem services: water for agriculture, rangeland management, drinking water and recharge. There is a need to take an integrated approach towards FBFS development by promoting multi-functionality, including making use of the agricultural potential. Changes needed to come to a sustainable multi-functionality are often not complex or costly but require good understanding of the local resource base, its carrying capacity and insights into opportunities for improvement.

**Keywords** Floodwater management · Floodplain agriculture · Groundwater recharge · Soil fertility · Ecosystem services

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## 1 Introduction

Agricultural systems have been traditionally classified into two categories: rainfed and irrigated (CAWMA 2007). This has left a huge gap in the middle, as many farming systems are neither rainfed or irrigated by perennial water sources, but are systems that depend on floods, i.e. flood-based farming systems (FBFS). While rainfed agriculture depends on rain and localized run-off, FBFS depends on larger flood events that may vary in intensity and duration from a few hours to a period of months. Flood intensity and duration determine the type of technique and flood management system used to most effectively and efficiently irrigate agricultural fields in a given command area (Garcia-Landarte Puertas et al. 2014).

One main category of FBFS is spate irrigation systems that depend on short duration floods in dry ephemeral rivers (Van Steenbergen et al. 2010). These floods are often forceful and unpredictable in nature and hence require special techniques and forms of organization amongst farmers to manage and distribute the large volumes of water. While perennial and supplementary irrigation unit flows will vary from 0.5 l/s/ha, up to in some cases 4 l/s/ha, spate irrigation unit flows can vary from a minimum of 10 l/s/ha up to 150 l/s/ha, depending on the size of both the catchment and command areas.

A second, more widespread FBFS category is floodplain cultivation in temporal or perennial rivers whereby land is inundated periodically (Tien and Ni 2014). Floodplain cultivation is relatively more predictable compared to spate irrigation. The most common form is flood recession farming, where the moisture that is left behind after a flood on the floodplain is used to grow crops. Flood rise farming on the other hand uses the rising flood levels to grow a crop, such as rice and sorghum varieties. A variation to this system is inundation canals, where ditches overflow when water levels in a river reach a certain level (Garcia-Landarte Puertas et al. 2014). In general, cultivation adjusts to the flood event rather than fully controlling it. To enhance their productivity, FBFS can be combined with the use of groundwater, which may be recharged by flood events.

FBFS in Sub-Saharan Africa (SSA) are extensive, probably close to 25–30 million ha (Tien and Ni 2014). They also are applied in Asia, particularly in Bangladesh, Cambodia, India, Myanmar, Pakistan, Nepal and Vietnam, as well as in the Middle East. In Asia, FBFS show a higher productivity and sustain larger populations compared to Africa. This is primarily related to a more intense management and multi-functional use of FBFS, which suggests the immense potential to increase productivity in African FBFS areas.

In developing FBFS, it is important to appreciate the numerous ecosystem services that are supported by floodplains, ephemeral rivers and natural depressions. Flood-dependent areas include valuable wetland functions (e.g. bird migration, ecosystem preservation, aquatic diversity, water quality). They also fulfil environmental (e.g. buffer areas in arid regions, $CO_2$ sequestration), social (floodplains are the livelihood base for rural communities), productive (FBFS described in this chapter) and microclimate functions (Tien and Ni 2014). Hence, there is a need to take an integrated approach towards FBFS development, including making use of the agricultural potential. Given the size of FBFS areas in Africa, their development constitutes one of the largest potentials for agricultural development in SSA. However, the needed techniques and approaches that are common in various Asian countries are little known in the region (Garcia-Landarte Puertas et al. 2014).

What is firstly needed are relatively low-investment and low-skill interventions that have the potential to increase floodplain agriculture resource efficiency. An example is the improved floodwater guidance and retention structures, drainage, flood-based aquaculture, special crop varieties and protected shallow groundwater wells in floodplains. In a next step, areas may be embanked to allow better control (Garcia-Landarte Puertas et al. 2014). In the case of spate irrigation systems, there is considerable scope to make better use of short-term floods in SSA. Particularly when more intense use is made of low-cost techniques, such as earthen diversion structures and bunds that guide floodwater over large areas. There is much scope to use run-off for farming, as well as for the cultivation of fodder grasses. However, FBFS tend to be ignored by development planners. It is not uncommon that hydropower projects or perennial irrigation systems are developed at the detriment of downstream FBFS, which may not be formally recognized and documented. This shows that their value is not appreciated (Garcia-Landarte Puertas et al. 2014).

This chapter aims to describe the diversity in FBFS, as well as their potential to facilitate agricultural development in SSA. It offers a variety of low-investment and low-skill tools that assist to increase the productivity of FBFS in Africa. Section 2 describes the FBFS categories, followed by the potential for FBFS development by improving water guidance, field water management, groundwater use and mapping and improving agronomic practices, multi-functional use and internal governance in Sect. 3. Section 4 concludes by offering a general recommendation on what social and environmental conditions are the best to exploit FBFS full potential in SSA.

## 2 Results

### *2.1 Flood-Based Farming Systems*

FBFS occur in areas that receive floods on a regular basis. These floods form the basis for productive farming systems, be it crop cultivation, livestock grazing or fishing grounds. Flood events can be of short duration, as in spate irrigation, or cover longer periods, like in riverine or lake side systems. The flooding pattern varies according to the topography and discharge from rivers or lakes. An important parameter is the sediment load carried by floods and how this is deposited. In FBFS, soils are alluvial and contain a range of material from fine clays to coarse gravel.

This determines the land use as well as the opportunities to use groundwater. The various FBFS categories described below, largely depend on the nature of flood and inundation use.

### 2.1.1 Floodplain Agriculture

This is the most common type of FBFS in SSA and may use receding and rising floodwaters for cultivation. Floodplain agriculture can be found in plains with gentle slope. Water levels rise as a consequence of rainfall in the catchment and rising rivers or lakes, after which floodplains are inundated. The sediment load in these flows is often high, carrying fine particles to the floodplains. Hence, floodplain soils have alluvial deposit (vertisols, fluvisols, gleysols and cambisols) with much fertile silt content. This type of farming occurs in areas along the Nile, Niger, Zambezi, Senegal, Lake Tana, Rufiji and Lufira rivers and their tributaries, being around lakes, along rivers and on the vast plains of South Sudan.

Flood recession agriculture uses the post-inundation residual moisture and fertile sediment for cultivation (Fig. 1). Therefore, crop varieties suitable for flood recession agriculture must tolerate semi-saturated soils and high groundwater tables at early stages. Crop selection may vary according to soil properties and flood conditions. Average flood recession soil textures are suitable for maize (*Zea mays*), sorghum (*Sorghum bicolor, Sorghum spp*.), millet (e.g. *Pennisetum glaucum*) and wheat (*Triticum spp*.), while more impermeable soils are suitable for flood recession rice. There are, however, also areas where crops are not grown on the receding flood but on the rising flood. Flood rising varieties are rice, such as *Oryza glaberrima* (African rice), *Oryza longstaminata* (endemic to most of SSA), *Oryza rufipogon* and *Oryza Barthii* (or African wild rice). In Central Africa, some sorghum varieties have also adapted to rising flood conditions.

A special feature in floodplains is dug-out ponds (Fig. 2). These are common to the White Volta sub-basin in Ghana (Ofusu 2011), as well as to the floodplains of South Sudan. Dug-out ponds are excavations in floodplains that are recharged by surface water coming from flood flows or run-off. They are normally located in depressed areas within the floodplain.

**Fig. 1** Flood recession around Witu, Kenya. *Photograph* MetaMeta

**Fig. 2** Initial stages of alluvial dug outs in Ghana. *Photograph* MetaMeta

**Fig. 3** Soil bunds preparation in Dera Ismail Khan, Pakistan. *Photograph* MetaMeta

### 2.1.2 Spate Irrigation

Spate irrigation is a form of water management that has been practiced in a variety of semi-arid environments across the world. During flood events, water from mountain catchments is diverted from normally dry riverbeds and spread over large areas for irrigation, improvement of grazing areas, filling of drinking water ponds and groundwater recharge. The unpredictable seasonal floods can last from a few hours to a few days. Their flow is guided over the command area with the help of soil bunds and flood channels to avoid erosion of the land (Knoop et al. 2012). It is a time-tested practice in Yemen, Pakistan and North Africa and has more recently expanded in East Africa.

Soil bunds (Fig. 3) can be several kilometres long, requiring much ingenuity during their construction. Key factors that need to be considered are the location, angle to the river bed, distance from the new diversion bund, soil from which they are made, compaction and the use of (brushwood) reinforcement. Given the high amount of collective work required, strong social cooperation and agreement on distribution of tasks are needed (Van Steenbergen and Mehari 2009).

As in floodplain farming, a characteristic of spate systems is the high sediment load, which can be up to 10% of the total weight. With the sediments, rivers bring along nutrients that help maintain soil fertility and build up land. On the other hand, sediment loads can also block intakes and channels and cause land to rise beyond what can be irrigated. Within spate irrigation systems, the management of sediment is hence a key component of floodwater management. An important strategy is to not divert those floods that are too large, as they carry large amounts of sediments, are often unmanageable, and increase the risk of gullying and degradation of the farmland (Knoop et al. 2012). Spate systems may vary in size from only a few ha to over 100,000 ha.

#### 2.1.3 Inundation Canals

Inundation canals are canals next to a river or floodplains that are fed by seasonal high water levels in rivers. They are either dug or formed by old creeks and off-shoots. They were common in ancient Egypt and can still be found in Sudan. In floodplains, the canals are used to facilitate water rising and receding flows.

#### 2.1.4 Depression Agriculture

Depression agriculture around seasonal wetlands is common in humid areas in West Africa, Southern Africa and Central Africa, where this is called dambos and bas fonds as well (Fig. 4). Dambos or bas-fonds are shallow, seasonally waterlogged depressions in the headwaters of rivers and streams (Chidumayo 1992). Located in the headwater zone, they have high groundwater tables and retain moisture for long periods. Their importance lies in the fact that they are widespread, can provide grazing in the dry season, and are moist enough to grow dry season crops without irrigation (Turner 1986).

### *2.2 Potential for FBFS Strengthening Through Knowledge Transfer*

FBFS are the livelihood base for numerous, often remote rural communities. They harbour an enormous potential to sustain higher yields of crops, livestock and fish, while providing more ecosystem services. The changes required are often not complex or costly, but require a good understanding of the local resource base and insights into opportunities for improvement. African FBFS can increase their productivity drastically by improving the following aspects:

**Fig. 4** Bas-fond in Senegal. *Photograph* MetaMeta

**Table 1** Relevance of different solutions for the various FBFS types

| | Flood recession/rise | Spate irrigation | Inundation canals | Depression agriculture |
|---|---|---|---|---|
| Water distribution | Relevant | Relevant | Relevant | |
| Field water management | Relevant | Relevant | | |
| Groundwater use | Relevant | | | Relevant |
| Agronomic practice | Relevant | Relevant | Relevant | Relevant |
| Internal governance | Relevant | Relevant | Relevant | |

1. Water distribution.
2. Field water management.
3. Groundwater use.
4. Agronomic practices.
5. Multi-functional use.
6. Internal governance.

The various solutions have a different relevance for each of the FBFS types. Table 1 gives a birds-eye view on the relevance of proposed interventions described in the remainder of this chapter.

### 2.2.1 Water Distribution

The challenge of spate irrigation is guiding large and unpredictable quantities of floodwater over sometimes extensive command areas. There is the risk that flows go out of control and cause erosion and rutting of land, particularly when command areas have considerable slope. Management of floods is achieved by dividing the floodwater into manageable proportions, avoiding steep slopes and by stabilizing flood channels and channel beds. Common techniques that can be used are as follows:

1. Flow division structures (Fig. 5), which are useful to keep flood flows manageable. Such structures need enough protection to avoid floodwater damage.
2. Drop structures that help to overcome level differences and dissipate energy (Fig. 6). Without such drop structures, floodwater may accelerate in certain sections of the command area and cause scouring. This can lead to canal and

**Fig. 5** Gabion flow bifurcation structure in Eritrea. *Photograph* MetaMeta

**Fig. 6** Stepped drop structure, Wadi Zabid, Yemen. *Photograph* MetaMeta

**Fig. 7** Flow division and channel bed stabilizer. *Photograph* MetaMeta

field gullying; destroying land and its capacity to retain moisture. Furthermore, flows could also move uncontrollably and even move out of the command area.

3. Bed stabilizers can be created with buried gabion structures of sufficient length, to avoid scour (Fig. 7). Bed stabilizers prevent that flood channels scour out and change position, making it difficult henceforward to control flood flows at those points.
4. Water spreading weirs reduce run-off and erosion. They are low retention walls that consist of a spillway in the actual river bed and later abutments and wings. As floodwaters rise, the various structural elements overflow one after another (Knoop et al. 2012).

To optimize the performance of spate irrigation systems, governments have often focused on investments to improve traditional systems and to construct new systems. These investments, however, sometimes undermined traditional water distribution and maintenance practices. Moreover, rather than coping with floods, they tried to control them, resulting in unexpected sedimentation and system failure and social conflict between upstream and downstream users.

Nevertheless, there is much scope to improve water distribution by putting in place water control structures within main flood canals and within the fields, to allow better control of water and reduce erosion or water logging.

### 2.2.2 Field Water Management

Particularly in floodplains, field water management is crucial to maximize productivity. Land cover is a key factor that causes alteration of flood rising and drainage. The lack of vegetation cover in floodplains is believed to increase the speed of flood rising and drainage (Hollis et al. 1993). Through better management of receding floods, water can be retained longer and moisture levels can be increased. Also, rising floods need to be regulated, to avoid damage at the basin level. Major dams in the river, which can regulate flooding patterns, should take into account land use and other anthropogenic factors to preserve flooding dynamics. Several of these interventions are mentioned:

- *Flood retention measures, dikes and soil bunds*: To protect fields from early, unexpected floods, bunds and small dykes can be constructed. This is especially relevant in places where farmers have sown flood rising rice varieties. Dykes can be equipped with wooden sluice gates to regulate flood inflow. Also, bunds may be laid to conduct flood flows to desired areas where the first floods are welcomed.
- *Flood staggering and retention measures*: At the plot level, farmers may build soil bunds before the flood season to help retain receding floods. Farmers can drain water in a controlled manner by using small cuts in the bunds. At floodplain level, large soil barriers are sometimes used to retain water or prevent livestock from entering the floodplain (as it is done in the Okavango delta). Similarly, dykes have been used in countries like Cambodia, Bangladesh and the Netherlands for centuries. In the case of Bangladesh, a sophisticated system of drains, dykes and gates help to stagger and control flood recession, also known as flood control and drainage systems (Wester and Bron 1998). Alternative flood retention methods can be found in Thailand, where 'monkey ponds' get filled by rising floods. After the floods recede, the ponds are used to supply water to surrounding fields.
- *Controlled drainage*: As floods are difficult to predict in time and intensity, it is advisable to optimize their benefits through adequate drainage systems. When floods are too intense, water shall be drained efficiently, to prevent damage to farmland and flood control structures. Drainage ditches are commonly used to channel away floods. They also help to evacuate water in saturated soils.
- *Reuse of flood water*: Field to field water delivery is a common practice in irrigation systems, particularly in South and Southeast Asia. Water that is used in the upstream is released to downstream users when water demands are met. In this way, downstream users can use the water from the same source. However, this system needs careful land levelling and common agreement on irrigation turns amongst water users. It is possible to combine shallow ponds with this type of irrigation.

### 2.2.3 Groundwater Use and Mapping

Shallow groundwater is a resource of great potential in FBFS as it can extend the cropping season in floodplains and depression agriculture. Floodplains normally have high water tables throughout the year. Hand dug wells have traditionally been the way to exploit groundwater. However, they are labour-intensive, demand considerable space and high maintenance costs.

Another way to approach ground water resources is by hand-drilled shallow tube wells. Hand drilling is an innovative technique that is still under development in Africa (see Table 2). Depths between 10 and 30 m are reached, which are enough to tap shallow groundwater. The manually drilled boreholes are of a small diameter. This makes it possible to seal wells with slab, apron and capping, making wells flood-proof and protecting them from pollution. Since this technology only requires local labour, the cost per drilled metre is significantly lower than mechanically drilled wells.

Water lifting technologies can be either manual or motorized, depending on water flow needs, depth of the groundwater table and financial viability. As floodplains are vast and sometimes remotely located, electricity is not always available. In addition, it is preferred to use light-weight pumps that can be moved easily, to prevent that pumps will be flooded or stolen. The following pumps exist:

- *Rope pumps*: These can lift water from a depth up to 35 m, and their construction and maintenance costs are low. The main disadvantage is that the flow is relatively low for irrigation purposes. Water delivery ranges between 0.17 l/s at 35 m depth and 0.67 l/s at 10 m depth (Olley 2008).
- *Treadle pumps*: Introduced as a low-cost technology for irrigated agriculture, their use has been handicapped by the arrival of motor pumps. The treadles serve as levers to pump up the water from a maximum depth of 7 m and require little maintenance. The total dynamic head is of 8 or 14 m, depending on the type. Water delivery is 1.4 l/s at 4 m depth (Olley 2008).

**Table 2** Potential for tube wells in floodplains of Mozambique

| | Technical suitability | Socio-economic suitability | Potential for tube wells |
|---|---|---|---|
| *Lower Zambezi* | | | |
| Riverine zone | High | High | High |
| Sofala plains | High | Low | Low |
| Zambezia plains | High | High | High |
| Coastal zone | Medium | Low | Low |
| *Lower impopo* | | | |
| Chockwe | High | Low | Low |
| Guija | High | High | High |
| XaiXai | Medium | Medium | Medium |
| *Inharrime* | | | |
| Inharrime plains | High | Low | Low |
| Pungwe | High | Low | Low |
| Save | High | Medium | Medium |
| Incomati | High | High | High |

- *Motor pumps*: Motorised suction pumps are the most popular pumping technology for small-scale irrigation in floodplains, since they are physically less demanding, widely available and easy to install. The maximum suction depth is 8 m; the total dynamic head is around 20–30 m. To reach groundwater that is situated deeper, the pumps can be installed inside a large dug hole. Since most smallholder farmers have smaller fields, they tend to run the pumps on a low rate that is not fuel efficient. An alternative is the use of micro-pump sets (Fig. 8). Their flow of about 3 l/s can be handled by smallholder farmers to irrigate fields of around 0.5 ha. Fuel consumption is more efficient, and with a weight of 10 kg, farmers can carry them home daily.
- *Solar pumps*: solar pumps are a cheaper, cleaner and more sustainable alternative to costly and polluting petrol pumps. The sunflower pump has been developed by Futurepump Ltd (http://futurepump.com/) and Practica Foundation, to provide smallholder farmers with an affordable and sustainable way to bring water to their fields. The solar panel captures the sunlight and converts it into electricity that drives the pump. The pump comes in a suction version (up to 7 m) and a deep-set version up to 20 m. The capacity on a clear day is maximum 13 $m^3$/day when lifting from 4 m to 4 $m^3$/day when lifting from 20 m. Capacity can be increased by adding a second solar panel.

Groundwater development across much of SSA is constrained by a lack of knowledge on the suitability of aquifers for borehole construction. Mapping groundwater potential zones is essential to plan the location of new abstraction wells that meet the increasing demand for water. The occurrence, distribution and movement of groundwater mainly depend on the geological and hydro-geomorphologic features of an area, particularly in terms of occurrence of sandy water-bearing strata (Gumma and Pavelic 2013). A complicating factor is that shallow groundwater resources mapping is different from the mapping of deep groundwater. Caution is needed to avoid uncontrolled use of groundwater. The risk of overexploitation in floodplains and depression areas is relatively low, however,


**Fig. 8** Chinese micro-pump set. *Photograph* MetaMeta

as annual flooding facilitates recharge, ensuring long-term availability of groundwater resources in these particular FBFS. The challenge lies in finding the right sandy or gravelly formations, as many FBFS areas have clay soils with little water.

### 2.2.4 Agronomic Practices

The high risk of crop failure associated with FBFS does not leave much space for classical improvements that are justified in intensive agriculture. There is, however, potential for production gains through introducing improving varieties and changing agricultural practices (Van Steenbergen et al. 2010). The large scope for this mainly comes from the neglect that has characterized FBFS system in agronomic research. With FBFS being risk prone and often very topical, there is more scope in exchange of varieties and agronomic practices between different areas with similar profiles and challenges.

The use of rising floods and flood recession in several areas in western Africa has permitted double cropping. As a first crop, rice or flood tolerant sorghum varieties are grown on rising floods and subsequently other crops, such as several varieties of pulses, are grown on the residual moisture. This improvement may offer opportunities for other areas as well, depending on flood rise patterns. In some areas, introduction of very fast growing floating rice varieties may be considered that keep up with the speed of the rising flood and can reach 3–5 m in height. Floating rice varieties grow in areas as varied as Mali and Vietnam.

Improved sorghum, rice, maize and varieties of other staple crops can boost agricultural performance. There has been comparatively little effort in breeding and agricultural research in FBFS, and more research is required on plant breeding under flood-based conditions. A starting point would be to systematically exchange and test varieties between different parts of the world where comparable FBFS exist.

### 2.2.5 Multi-functional Use

The potential of FBFS and floodplains in general can be optimized with interventions that fall outside of the agriculture realm and serve the multiple uses of floodplains that have been traditionally occurring, such as fishery, flood pastures, fuel wood collection and water supply. For instance, intensive re-greening and watershed management interventions in FBFS areas of the Raya Valley in Northern Ethiopia could optimize the use of floods to provide and regulate ecosystem services such as an increased biodiversity and natural vegetation. Floods could give a considerable added value to local communities as additional income sources become available through the revitalization of grass and bushland for livestock, groundwater recharge, the birth of springs and a reduction in the occurrence of damaging flood events.

One major particular important use of FBFS areas is fishery, particularly in flood rise and flood recession systems. Fish culture requires less inputs for protein production compared to agriculture, in terms of fertilizers and fodder (Maar et al. 1966). Hence, aquaculture in SSA poses great potential to improve diets and food alternatives. Aquaculture and controlled fishery in Asian FBFS areas are very much part of the resource system. A popular practice is to build ponds in floodplains, which are used to raise fish species that are brought by floods or selected to be raised as fish species. There are three main types of inland floodplain ponds used for fish aquaculture, being contour ponds, finger ponds and paddy ponds.

- *Contour ponds*: These are ponds laid in dambos or valley sides along gentle slopes and are fed by streams or conservation dams. Barrage ponds are ponds commonly set in dambos and are set as a series of ponds where each pond overflows and feeds the following one (Maar et al. 1966). All barrage ponds can be fed by a single furrow.
- *Finger ponds*: These can be laid in the vicinity of lakes and rivers. They are meant to trap fish under flood rising conditions, and once floods retreat, the fish gets trapped and is raised until they reach optimal weight and size for the market. Finger ponds can be found around Lake Victoria, East Africa (Van Daam et al. 2006).
- *Paddy ponds*: A third type is the paddy pond, which is laid over flat surfaces of dambos or floodplains. Four walls are set to construct these ponds, as opposed to three walls of contour ponds or one wall of barrage ponds. Water is distributed through furrows on top of the ponds. Water usually comes from a spring or seepage area. Apart from fish ponds, wild fishing activities are carried out in floodplains. Fish culture in floodplains is based on migration of fish to flood rising areas or fish retreating to lakes and riverine environments under flood recession, with species like *Clarias spp* spawning in floodplains. Catfish are known to be the first species to spread through floodplains and are the last to leave as well. Sardine species (*Alestes spp*) are more sensitive to changing water levels and are the first to go back to the rivers and lakes. Therefore, sardines are fished using shaped traps and dragnets when they retreat to rivers in mass numbers. Other techniques involve the digging of channels next to rivers. Nets are placed in channels trapping fish heading back to rivers, especially for *Clarias spp* and *Tilapias spp*. Other floodplain uses are as follows:
- *Flood pastures*: Pastoralists use recently flooded areas for cattle grazing as floodplains often provide extensive grassland areas that are ideal for this purpose. A number of plant species are well-adapted to flood rising and flood recession conditions. Plant species such as wild rice (*Oryza glaberrima*), Borgou (*Echinichloa stagnina*), *Sporobolus robustus* grass and *Vossia cuspidata* form the basis for productive pasture land, as in the Niger Inner Delta in Mali (Zwarts et al. 2005). Pastoralists normally bring their herd after floods retreat, when grasses have the best nutritious conditions for livestock feed.
- *Timber, fuel wood and leave harvesting*: Forest and bushlands are common in plains that flood temporarily. These are extensively used as a source of fuel

wood and leaf harvesting by rural communities. This is particularly so when the communities are located in remote areas with poor electricity and road connection. Apart from timber products, certain leaves are harvested, such as those of the Doum palm (*Hyphaene thebaica*) in the Hadejia-Nguru floodplain (FAO 1997). These leaves are used for mat, rope and basket production or sold as raw material. Baobab leaves are also collected for diet purposes. Baobab leaves are considered to be 'drought food' and are used in soups and stews during the dry season. Similarly, *Sporobolus robustus* and *Acacia nilotica* are harvested in the Senegal River valley. They are harvested by women and used for mat making. It has also been suggested that the ubiquitous reeds could be used for the production of briquettes.

- *Drinking water and groundwater recharge*: Small prisms of fresh water stored in the bed of the spate rivers can be an important source of domestic water supply in areas that have saline groundwater and where locally specific recharge measures can be undertaken (Van Steenbergen et al. 2010). Furthermore, improvements to drinking water options may be made by creating water ponds for human and livestock use. These water ponds may secure water supply for a number of months after the flood season. Even though they will provide water of low quality, in many areas, there is no alternative (Van Steenbergen et al. 2010).

### 2.2.6 Internal Governance

It is clear that FBFS have a broad scope for alternative uses of water resources. Unfortunately, FBFS have not received the necessary attention by governments, donors and development agencies. The blind spot is closely related to a lack of understanding and appreciation of how these systems work, and consequently, their potential for agricultural development. In view of the extent and potential of FBFS, this should be corrected. To increase its potential, the role of governments in FBFS development must be strengthened. Policy-makers, decision-makers and governmental authorities must become familiar with FBFS. Awareness campaigns and trainings can enable them to understand and use techniques and approaches linked to FBFS. Regulatory policy on land and water access in dry and wet seasons can accommodate various needs amongst different floodplain users. Apart from supporting farmers and other floodplain users, extension officers could monitor and evaluate the performance of FBFS at a medium scale. This information can help decision-makers to formulate strategies that are adapted to flooding patterns, changing rainfall events or migration fluxes.

Likewise, there is great need to include FBFS in university curricula, as these systems are still largely unknown to agronomists and engineers. New engineering principles which consider FBFS as alternative and unique systems are required. Engineers and water professionals must acknowledge the intrinsic characteristics of FBFS and elaborate design standards accordingly. At the field level, practitioners, entrepreneurs and model farmers need to be approached and involved to consolidate knowledge and expertise on FBFS. Thus, human capital is one of the main challenges and goals to strengthen and exploit the full potential of FBFS.

## 3 Discussion

The flood-based farming systems described in this chapter can integrate the multiple targets and needs that exist in the field of climate change, biodiversity preservation and resilient livelihood creation. Livelihood components that need to be strengthened are mainly flood-based aquaculture, the use of special crop varieties and the cultivation of fodder grasses. Good opportunities are provided by the relatively low-investment and low-skill interventions that are mentioned in this chapter and which have potential to increase floodplain agriculture resource efficiency. However, FBFS and floodplain management in general should also be optimized with interventions that fall outside of the agriculture realm and that serve the multiple uses of floodplains that have traditionally been occurring.

FBFS are not only of significance from a productive perspective in the world's marginal semi-arid areas; their importance also should be sought in the environmental realm. Flood-dependent areas harbour valuable wetland functions like migratory bird shelters, aquatic diversity and water quality. They are key agents in the regulation of local and global climates as well, through $CO_2$ sequestration for instance. There is a need to take an integrated approach towards FBFS development by promoting multi-functionality, including making use of the agricultural potential. Changes needed to come to a sustainable multi-functionality are often not complex or costly but require good understanding of the local resource base, its carrying capacity and insights into opportunities for improvement.

## 4 Conclusion

Floods are often regarded as harmful and destructive. However, they have positive impacts as well and provide useful services to rural communities across Sub-Saharan Africa. With an estimated 25 million ha under FBFS and a mean plot size of 0.5 ha, it can be assumed that about 50 million people directly use and benefit from these systems. If we include pastoralist communities, and other people who indirectly benefit from these systems, i.e. through food provision, the number increases substantially. FBFS not only represent potential productive systems; they also provide resources to accommodate food security and income generation in remote areas of Africa. It thus becomes clear that FBFS need to receive greater attention in terms of improvement, research, investment and inclusion in strategic policy development.

FBFS require good management practices and knowledge on flood behaviour to maximize benefits from those floods. For this reason, more attention has to be brought on capacity building and agricultural extension services through educational and training centres. Human capital is one of the main challenges and goals for strengthening and exploiting the full potential of FBFS. Likewise, practitioners and entrepreneurs willing to implement new technologies must have financial and institutional support.

At the moment, FBFS are predominately used to ensure food security. Yet, there is potential to manage these systems for small-scale farmers as a means to earn profit and become more entrepreneurial. There is still room for farmers to try new crops and cultivars, use alternative technologies to increase productivity and become more market-oriented to optimize FBFS as productive systems. However, assistance from extension workers and supporting institutions is needed for small-scale farmers to become more entrepreneurial. To improve productivity, planning and interventions should focus on multi-functionality, which has both a spatial and temporal characters. A field can be used for fisheries or rice cultivation in the wet season and for vegetable cultivation in the dry season. Such an approach requires flexibility from farmers but also from techniques used.

Interventions which require further development are the optimization of shallow groundwater use through manual drilling, shallow wells, affordable pumping technologies and groundwater development maps that indicate the availability of groundwater resources. Such interventions should, however, be embedded in a wider floodplain-level water management plan including improved flood management and drainage systems, agronomy of flood tolerant and flood recession varieties, floodplain fishing culture and alternative uses for floodplain resources.

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# Adaptations in Water Harvesting Technologies for Enhancing Food Security and Livelihood: A Multi-country Study in Sub-Saharan Africa

**D. Snelder, F. Kahimba, O. Korodjouma, A. Abebe, E. Oughton, L. Bunclark and R. Lasage**

**Abstract** The objective of this paper was to examine farmer-directed technology adaptation of selected water harvesting technologies (WHTs) in order to enhance their potential contribution to food security and livelihood improvement in sub-Saharan Africa. The selected WHTs included micro- and meso-scale reservoirs that store water in the soil (in situ) or in a reservoir, respectively: household ponds in Ethiopia, ndiva systems in Tanzania and combinations of mechanized zaï, grass strips and bunds in Burkina Faso. The impact of non-adapted WHTs was below expectation. Although WHTs improved yields, most families were unable to meet their (nutritional) food needs every year and experienced limited or no long-term effects on sustainable livelihood. The lining of household ponds and conveyance canals with durable materials gave promising results, yet needs economic consideration; a minimum investment may form a barrier particularly to resource-poor farmers. Incorporation of the location-specific nature of farming and livelihoods into WHT interventions is recommended, along with incentive measures to support farmers including the provision of access to credits and inputs for agricultural production.

**Keywords** Ponds · Ndiva · Zaï · Bunds · Arid and semi-arid areas

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## 1 Introduction

One of the major challenges for Africa is to address the vicious cycle of poverty and food insecurity by promoting agricultural growth in general and increasing productivity per unit area in particular. Earlier studies (CA 2007; World Bank 2007) reveal that farmed areas that rely on natural rainfall rather than irrigation for water have significant potential to be improved thus increasing agricultural productivity. This is especially the case in rural semi-arid and arid areas of sub-Saharan Africa. At present, the productivity in these areas is constrained by highly variable rainfall and frequent dry spells, making rainfed farming a risky undertaking. An estimated 70–85% of the rainfall on sub-Saharan dryland farms is lost through non-productive evaporation, surface runoff and deep percolation (Rockström 2000).

Water harvesting technologies (WHTs) represent a key intervention to control water losses and strengthen productivity of rainfed agriculture in these areas. Mekdaschi Studer and Liniger (2013, p. 4) define water harvesting as, "the collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance".

The harvesting of rain, runoff and floodwater for enhanced crop growth is a key strategy through which increased sustainable food production and security can be achieved in semi-arid and arid regions of sub-Saharan Africa. WHTs have been traditionally used in these regions (e.g. Critchley and Gowing 2012) where either pure rainfed or full irrigation agriculture was not an option for a number of socio-economic (e.g. lack of capital and resources), topographic and biophysical reasons (e.g. distance to water source, drought and soil constraints; e.g. Rockström and Falkenmark 2015). WHTs are particularly important in bridging dry spells, which, in turn, can lead to significant increases in productivity. For example, Bouma et al. (2016) found an average yield increase of 80% based on a meta-analysis of 221 field studies of crop yield impacts of water harvesting in semi-arid Africa and Asia.

However, the applicability and impact of water harvesting vary with technologies and local conditions. For example, Mekdaschi Studer and Liniger (2013) report a clear increase in yield and income in areas where floodwater harvesting is practised, whereas such an improvement is not always evident in areas where other forms of water harvesting are used (i.e. macro- and micro-catchment water harvesting and rooftop water harvesting). Their findings are based on an analysis of 60 case studies of water harvesting worldwide derived from WOCAT (2012).

In order to sustainably enhance food production and security, now and in the future, there is a need for WHT adaptation to account for environmental, economic and demographical changes. This chapter reports on some of the main findings of the EU-funded project "WHaTeR" (2011–2015) set up to contribute to the development of sustainable WHTs for strengthening rainfed agriculture and rural livelihoods in sub-Saharan Africa (Critchley and Gowing 2012).

The main objective of this study was to examine technology adaptation of selected WHTs in order to enhance their potential contribution to food security and livelihood improvement in the sub-Saharan region. Technology adaptation refers to a technology that is changed (improved) and tested so as to become suitable to a new condition (associated with environmental, economic or demographical changes). The following questions were addressed: what is the current status (performance and constraints) of the selected WHTs, what is their impact on food security and livelihood and what are the effects of (farmer-directed) field interventions aimed at technology improvement of the selected WHTs? The WHTs in this study included micro- and meso-scale reservoirs that store water in the soil (in situ) or in a reservoir, respectively, with or without a combination of fertilization and soil management technologies: household ponds in Ethiopia, ndiva systems in Tanzania and combinations of mechanized zaï, grass strips and bunds in Burkina Faso.

The sections below begin with an overview of the sites and the selected WHTs in the case study countries, followed by the main results of the current WHT status, the impact on food security and livelihood and the field interventions for technology improvement, based on the data gathered at multiple sites in the three countries. The main results lead to the discussion and finally the conclusion.

# 2 Methodology

## *2.1 Study Area*

The study was conducted between 2011 and 2015 at multiple sites in three countries representing different parts of the sub-Saharan region, i.e. Ethiopia in the northeast, Tanzania in the east and Burkina Faso in the west of Africa (Fig. 1: location in study sites in three countries in one map). The criteria for country selection were the presence of WHTs and the presence of sites with distinct hydrological, biological and socio-economic conditions representative for sub-Saharan Africa, including lowland and upland areas in east and west Africa.

### 2.1.1 Climatic Conditions

Semi-arid-to-arid conditions prevail in all three study areas (Table 1): the average annual rainfall is in the range of 500–1100 mm, with the highest values recorded for Péni in Burkina Faso and Alaba in Ethiopia and the lowest for Makanya in Tanzania (Table 1). Yearly potential evaporation rates greatly exceed annual rainfall depth, indicating water deficiencies during at least part of the year. The longest dry season (up to eight months) is noted for Boukou in Burkina Faso where uni-modal rainfall patterns occur. The latter means that most rainfall is concentrated in a relatively short period with the rest of the year virtually dry. Similar conditions of water deficiency occur in the study area in Tanzania (Makanya and Bangalala),

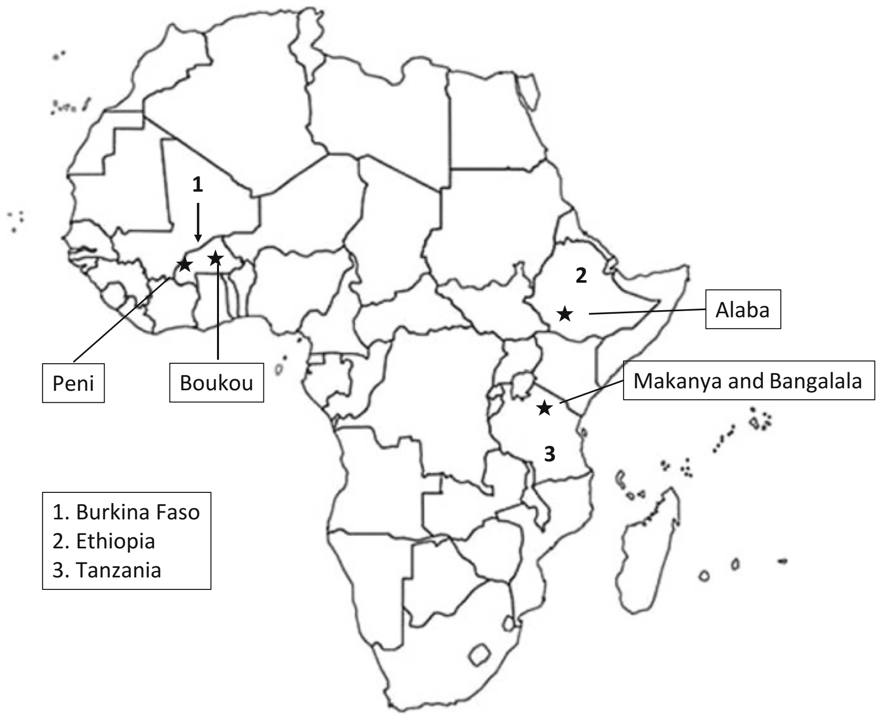


**Fig. 1** Location of the study sites in Ethiopia, Tanzania and Burkina Faso

**Table 1** Overview of the case study areas and associated climatic conditions in each of the three countries in sub-Sahara Africa

| Climate variable / Case study area | Rainfall pattern (uni or bi-modal) | Average rainfall (mm $y^{-1}$) | Length dry season (months) | Average potential evaporation (mm $y^{-1}$) |
|---|---|---|---|---|
| *Ethiopia* | | | | |
| Alaba | Bi-modal | 850–1100 | 7 | 1750[a] |
| *Tanzania* | | | | |
| Makanya/Bangalala | Bi-modal | 500–630[b] | 6 | >2000[c] |
| *Burkina Faso* | | | | |
| Boukou | Uni-modal | 600–900 | 8 | 1600–2000 |
| Péni | Uni-modal | 1000–1100 | 5 | 1000–2800 |

[a]Shewangizaw and Michael (2010)
[b]For whole Makanya catchment, the 1960s to 1990s average is 500–630 mm based on same station; Mul et al. (2006)
[c]Sally (2010), Mul et al. (2006)

although here the duration of the dry season is shorter (i.e. six months) and rainfall is distributed over two, rather than one, seasons.

### 2.1.2 Water Harvesting Technologies

The study addressed different types of WHTs in each of the three countries (Table 2). The criteria for selecting WHTs included: a common occurrence within a country; the need for improvement; opportunities for uptake and upscaling; and the inclusion of a range of water harvesting technologies that store rain and runoff water either directly in the soil or in reservoirs of different size and format, constructed inside or outside the cultivated fields, or a combination of both.

In Ethiopia and Tanzania, the selected WHTs were meso-reservoirs mostly located outside the fields supplemented with the reservoir water. In Ethiopia, the focus was on household ponds owned or managed by individual farmers (pond storage capacity: up to 300 $m^3$). In Tanzania, the so-called ndiva was object of study, supplying water to multiple fields of various households or a community (pond storage capacity: up to 2000 $m^3$). In *Burkina Faso*, the study covered small-scale WHTs combined with soil fertility and management technologies ($WHT^+$): in situ storage measures (earth bunds, stone bunds, grass strips), infield micro-reservoirs (mechanized zaï, also called planting basins or pits) and organic, compost and/or NPK and urea fertilization. The combination of technologies was tested based on reports in the literature that more promising yields can

**Table 2** Overview of the water harvesting technologies selected for field studies between 2011 and 2015 and classified by country and type of water storage

| Country | Type of water storage[a] | Water harvesting technology |
|---|---|---|
| Ethiopia | Meso-reservoir storage outside field | Household pond[b] |
| Tanzania | Meso-reservoir storage outside field | Dam with reservoir and canals (ndiva system)[c] |
| Burkina Faso | In situ storage | Earth bunds[d] with contour ploughing |
| | Micro-reservoir storage inside field, in situ storage | Mechanized zaï[e] with stone bunds[f] |
| | Micro-reservoir storage inside field, in situ storage | Mechanized zaï[e] with grass strips[g] |

[a]With size details in numbered footnote
[b]Household pond volume: 30–300 $m^3$ (see, e.g. Tesfay 2011); ratio catchment : crop area > 5
[c]Reservoir volume of 200–2000 $m^3$; ratio catchment area : crop area > 5
[d]Earth bund width: 80 cm, height: 30 cm; spacing: 33 m; ratio catchment : crop area <5
[e]Micro-reservoirs, also referred to as micro-catchments or pits, with diameter of 24–30 cm and depth of 15–20 cm; ratio catchment : crop area < 2
[f]Spacing stone bunds: 30–50 m, depending on soil and slope
[g]Grass strips: 1–4 rows of *Andropogon gayanus* per strip with row spacing of 10 cm; strip spacing: 30–47 m; ratio catchment : crop area < 5
*note* The ratio catchment : crop area after Critchley and Gowing (2012)

be achieved by combining water harvesting with fertilizer application (e.g. Winterbottom et al. 2013).

## 2.2 Methods

### 2.2.1 Case Study of Household Ponds in Ethiopia

The study in Ethiopia was conducted in the Alaba district (woreda), located in the Southern Nations, Nationalities and Peoples Regional state (Fig. 1). Water deficits affect food production in the district, whereas geo-environmental conditions hinder access to supplementary water sources; surface water is too far away for most villages while groundwater levels are generally at a depth of over 200 m (Abdela 2014). Hence, household ponds are expected to form (part of) a solution to the water deficit in the district, providing nearby water for domestic purposes, livestock watering and small-scale supplemental irrigation of crops (fruits and vegetables) during short dry spells in the growing season. However, multiple cases of pond failure (due to, for example, poor location and construction) are reported in the literature (e.g. Rämi 2003; Lemma 2005; Segers et al. 2008; Moges et al. 2011; Lasage and Verburg 2015).

A total of 145 household ponds (average storage capacity: 60 $m^3$) were selected in twelve municipalities of the Alaba district to assess the current status of ponds and test methods for reducing pond seepage and evaporation losses. At the start, information was gathered among pond holders (36 with concrete pond, two with geo-membrane pond and the rest—60—with earthen pond) on the current status of ponds and methods for pond improvement. Then, detailed measurements were taken on a selected number of ponds, i.e. nine cement-lined, nine geo-membrane and two earthen household ponds from three municipalities. In addition, an on-farm 72-day experiment was set up in the municipality Wanja (Alaba district) to study the water storage efficiency of square ponds with different lining materials: two lined with clay soil (sandy clay loam; pond storage capacity: 83 $m^3$), two lined with termite-mound soil (sandy clay loam; 83 $m^3$), two lined with soil and cow dung (sandy loam; 83 $m^3$), one lined with cement (47 $m^3$), one lined with geo-membrane (56 $m^3$) and one control pond (no lining material used; 83 $m^3$).

An additional survey was conducted among a total of 300 pond-holding households with good (154 interviews) or poor market access (146 interviews) to determine households' socio-economic condition and their perception of pond benefits and constraints (particularly in terms of livelihood and food security), pond maintenance and pond continued existence.

### 2.2.2 Case Study of Ndiva Systems in Tanzania

The ndiva system in Tanzania is typically practised in areas with frequent dry spells and increased pressure on water resources due to a growing population. It consists of a reservoir, an embankment or micro-dam, and a system of canals to convey water from reservoir to field. The reservoir allows temporary storage of rain and runoff water for supplemental irrigation. The micro-dam, built at the lower side of the reservoir from earth (usually soil excavated for reservoir construction) or concrete material, serves to increase the storage volume of the reservoir. The latter may range from 200 to 1600 $m^3$ (Mul et al. 2011). Located outside the cropped fields and adjacent to high or midland areas, the ndiva reservoir can harvest water also at times when there is no rainfall in the cropped area itself (Gowing et al. 1999). Various studies (e.g. Hatibu et al. 2000) report, however, problems of water losses due to evaporation and seepage and siltation, affecting the ndiva system capacity and hindering the provision of water to all farm fields and households in need.

The study in Tanzania was conducted in the Makanya catchment, Same district (Kilimanjaro Region, northern Tanzania; Fig. 1). The farmers of Bangalala village (located in the highlands upstream of Makanya village) store headwater streamflow in small-scale ndiva reservoirs overnight for irrigation of all crops during the next day, using the associated conveyance canals. However, the ndiva system suffers from conveyance losses that occur when water is being transmitted through the irrigation canals. These losses can be as high as 80%, implying that downstream fields located at long distances from the micro-dam reservoir may receive only 20 mm per field per season which is insufficient to overcome seasonal dry spells (Makurira et al. 2007). The average distance between a ndiva reservoir and associated fields supplied with water is 500 m (range: 30–3000 m). Depending on the reservoir's storage capacity and the canals' efficiency in conveying water from the reservoir to the fields, a ndiva system can serve one or more villages and irrigate an area of 50–150 ha.

The field interventions on the ndiva system, aimed at reducing the water losses from conveyance canals, were conducted between July 2012 and June 2014 in the semi-arid midlands and lowlands of the Makanya catchment. Firstly, the existing ndiva systems were examined in more detail in order to better assess current constraints. Based on this knowledge, methods for technology improvement were developed in consultation with local communities. These included innovations for increasing the system's functional efficiency such as the lining of the conveyance canals by stone pavements for which local communities provided in-kind contribution. V-notch weir and float methods were used to measure canals flow discharge while the waterfront was used to get the estimates of the velocity of water in the canals. Structured questionnaires and focus-group discussions were conducted to evaluate farmer's knowledge and perceptions on the performance, operation, maintenance and effects of the ndiva systems.

### 2.2.3 Case Study of Combinations of Mechanized Zaï, Grass Strips and Bunds in Burkina Faso

Burkina Faso has a long history of governmental and non-governmental organizations actively promoting the use of soil and water conservation technologies, including water harvesting through earth bunds, stone lines and zaï pits (used solely or in combination). The popularity of WHTs among organizations in, for example, the 1970s and 80s was attributed to WHTs providing visible improvements to agricultural productivity in the short term and organizations receiving external support for the construction of water harvesting structures (Kaboré and Reij 2004). Yet, WHT performance, uptake and impact remained below expectations in various parts of the country, suggesting farmers not always shared the organizations' optimistic views on WHTs. This notion led to on-farm experimentation, i.e. a process whereby WHT testing is undertaken on farmers' field for local adaptation and improved performance, which eventually can lead to a more widespread uptake.

The case study in Burkina Faso addressed a combination of small-scale WHTs including mixed micro-reservoir and in situ storage of rain and runoff water for impact maximization in terms of food production and livelihood. Household surveys were conducted to examine the current status, in terms of (lack of) uptake and adoption of the different water harvesting technologies, and their impact on food security and livelihood, at two sites in two distinct climate zones: Boukou in a lower rainfall zone (centre region) and Péni in a higher rainfall zone (south-west region; Table 1). Based on the outcomes of the surveys, on-farm tests were conducted at each site for different technology combinations ($WHT^+$) including water harvesting (mechanized zaï), fertilization, bunding (earth and stone bunds). Effects on soil quality and crop yield were assessed and associated costs and benefits of the different technologies were determined.

The combinations of technologies used for on-farm testing (Fig. 2) include:

- *Mechanized zaï* (MZ; diameter: 24–30 cm; depth: 15–20 cm) made with the use of a small (8 or 12 mm) ripper drawn by cattle or a donkey, in association with *stone bunds* (CP) along the contour line across fields with a spacing of 30–50 m, the exact distance depending on slope and soils type;

**Fig. 2** Field with grass strips (left), mechanized zaï (middle) and zaï with stone bunds (right), Burkina Faso. *Photographs* Issa Ouedraogo and Korodjouma Ouatarra

- *Mechanized zaï* (MZ) constructed in combination with *grass strips* (BE) of *Andropogon gayanus* along the contour line across fields with a spacing of 30–47 m between strips and one to four rows (row spacing: 10 cm) of *A. gayanus* per strip;
- *Earth bunds* in association with *contour line ploughing* (ACN).

The criteria for selection of water harvesting, fertilization and soil management technologies included: the presence of stones or *Andropogon gayanus* grass (the former determined by geological formation, the latter by climate); the technologies indicated on the soil and water conservation technologies map for the area; the evaluation results of research institutes (Zombré 2003; Zougmore et al. 2004); the WHaTeR's revisit study (Critchley and Gowing 2012); and the farmers' preference as the last weighting criteria (farmers choice determined at last the technologies to use).

# 3 Results

## *3.1 Household Ponds in Ethiopia*

### 3.1.1 Current Status

Figure 3 shows examples of the three types of ponds assessed in this study, i.e. concrete (with or without cover), geo-membrane plastic and earthen household ponds.

It should be noted that only two households had ponds with geo-membrane plastic lining material at the time of data collection. Moreover, households reported that none of the earthen ponds (4000 in total) installed through a government programme between 2003 and 2006 were still in use; the ponds were converted into cultivated land or used as garbage pit (Abdela 2014). The ponds were to be cemented at a later stage (requesting ca 1200 kg cement per 60 $m^3$ pond; Abdela 2014). However, just 10,000 quintal (1,000,000 kg) of cement was delivered, which was partly used for other purposes, resulting in the construction of only 198 concrete household ponds due to cement shortage. The remaining were left as "earthen" ponds, which in time were functioning poorly (Abdela 2014). The study revealed other factors that limited pond performance, explaining why many ponds were not in service or functioning far below capacity (see Table 3). The reason for pond adoption failure, most often reported by households, was insufficient or no involvement of communities during the pond planning and implementation processes.

**Fig. 3** Household ponds in Alaba, Ethiopia: a trapezoidal pond lined with geo-membrane. Plastic for seepage control (upper left); a recently established earthen pond (upper right; a concrete pond with corrugated iron cover to reduce evaporation losses (lower left) and a non-functioning concrete pond without cover (lower right). *Photographs* Adana Abebe Awass and Hussen Abdela

### 3.1.2 Impact on Food Security and Livelihood

The promotion of household ponds through government programmes has been a government strategy since the late 1990s (e.g. Seyoum 2003; Rämi 2003) to alleviate poverty, improve livelihood and enhance food security among smallholder farmers. In this study, the households with a concrete pond produced for the market, whereas those with other ponds, or with non-functioning ponds, only produced for household consumption. The main crops grown with pond water included cabbage, pepper, onion, coffee, potato, avocado, mango and chat. Among the 155 households living near a road, 89% believed that a pond increases yields; 74% believed that it improves food security; and 82% believed that it improves the value of crops; for the 145 households living far away from a road, the results were less positive, i.e. 56, 65 and 65%, respectively. Households referred to pond benefits not only in terms of higher crop revenues but also in terms of savings from noticeable reductions in labour costs due to improved access to water (no need to fetch water from distant sources).

Yet, despite perceived yield benefits of ponds, 49% of the 300 households in total lost most of their harvest once every two years due to lack of (rainfall) water;

**Table 3** Factors limiting the performance of household ponds in the Alaba district, Ethiopia

| Limiting factor | Description |
|---|---|
| Pond location | Some ponds were located above (at higher elevation) the runoff generating area<br>Some ponds were fed with sediment-rich water originating from catchments with a steep gradient, resulting in siltation and reduced pond capacity |
| Pond construction | Inappropriate use of construction material (e.g. cement for non-pond purposes leading to cement shortage and poorly lined reservoirs (Fig. 3—lower right))<br>From the sample of 36 households with a cement-lined pond, 76% were not functional at the time of data collection (Abdela 2014) |
| Water loss | Ponds suffered from leakages and, except for ten ponds constructed by Sasakawa global (Fig. 3—lower left), no pond had a cover to control evaporation |
| Water abstraction device | Lack of safe water abstraction mechanism; no ladder nor steps to access the water in the pond; use of traditional water lifting systems (bucket and rope) |
| Fencing | Household ponds were not fenced leading to accidents with livestock and children and affecting water quality where drowned animals were left to decay |
| Pond maintenance | 70% of the households in this study did not clean their pond at all<br>Silt traps decreased 0.7 m in depth on average, some being totally silt-covered<br>Various ponds spread poor odour due to stagnation of water on cover sheet<br>Use of corrugated iron covers and geo-membrane plastic sheets was less than expected, the materials being “stolen or used for other purposes” (e.g. roofing; Fig. 4) or “damaged and removed” (hyena’s accessing ponds for drinking destroyed geo-membrane sheets) |
| Community involvement | Insufficient involvement of communities in pond planning and implementation resulting in a lack of ownership, maintenance and public awareness |

on average, € 147 (stand deviation: 118) is being lost per household in a year. As coping strategies, 64% of the households grow at least four different crops, 61% practise consumption reduction and 28% engage in off-farm activities to generate extra income when there is drought or lack of rainfall. Only 55% of the households had access to credit and only 24% received remittance from relatives or close friends. Nevertheless, after witnessing economic benefits among pond adopters, most farmers were motivated to construct ponds even without assistance from the government.

The study also examined factors influencing continued existence of household ponds, i.e. whether a pond is still functioning at some time (e.g. one year or more) after initial adoption. Both “trust in authorities” (79–86% of the households; this variable was included based on reports of project successes and failures affecting households’ trust in authorities) and the perception of ponds reducing risks of crop losses (75–89%) have a significant impact on the likelihood that a pond is still functioning, as is the number of livestock (Tropical Livestock Unit) owned by a household (average TLU: 4.6 and 6.6 for, respectively, households far away from any road, i.e. with poor market access, and those near a road, i.e. with good market access). Moreover, ponds financed by the government are maintained less well than ponds financed by NGOs or the households themselves. Other factors with significant impact on continued pond existence relate to pond quality (i.e. lining and maintenance of pond), technology perception (i.e. a pond reduces crop loss), location near a road and perceived market access. Non-lined ponds fall apart more easily and non- or poorly maintained ponds become dysfunctional. The importance of "location near road" is also evident from the 66% of the ponds near a road still functional as opposed to only 33% of those located far from a road. Finally, perceived market access ("good" according to 62% of households near a road and 28% of those far from road) proves to be important for longer-time pond adoption, allowing farmers to shift to the production of higher value crops in order to increase their income.

### 3.1.3 Pond Improvement: Use of Different Lining Materials

The 145 household ponds selected for status assessment (Sect. 3.1) differed in lining materials, i.e. concrete (cement), geo-membrane plastic and earth, resulting from different projects operating in the past. Compared to concrete lining material, geo-membrane plastic was relatively cheap and easier in application (i.e. requesting no technical expertise).

The results of on-farm testing of different lining materials in ponds, reconstructed with the assistance of farmers from previous non-functioning ponds, are presented in Fig. 4.

Concrete and geo-membrane lined ponds had higher storage efficiency than ponds with locally available lining materials, e.g. termite-mound soil. Storage efficiency decreased, with increasing seepage and evaporation losses over the test 72-day period, from 100 to 97% for geo-membrane ponds, 84% for cement ponds, 28% for ponds lined with termite-mound soil, 24% for those lined with clay soil, 19% for those lined with soil–cow dung and 12% for the control pond. Cumulative seepage losses were the highest for ponds lined with soil and cow dung (63–65 $m^3$) and the lowest for ponds with cement (4 $m^3$) and geo-membrane plastic (0 $m^3$); the loss from the control pond was 70 $m^3$. The seepage losses were measured by continuous monitoring of water levels in the household ponds and evaluating the associated water balance. Cumulative evaporation losses were the highest (3.89 $m^3$) for ponds lined with termite-mound soil and the lowest (1.02 $m^3$) for those with cement. The evaporation losses, measured with pan evaporimeter installed in the surrounding area, varied among treatments mainly due to the difference in surface area at different levels of the pond.

Total costs (including costs for labour and materials made in 2013) and effective costs (per $m^3$) varied from, respectively, € 154 and € 10 for ponds lined with soil

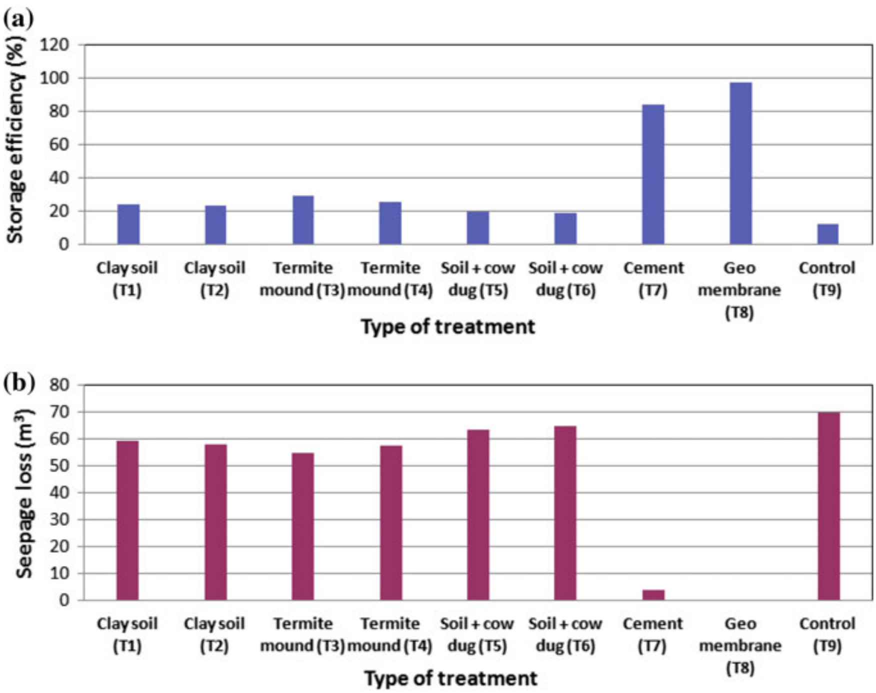


**Fig. 4** Type of pond treatment (different lining materials) and corresponding **a** storage efficiency (%) and **b** seepage loss ($m^3$) for ponds tested over 72 days in Alaba district, Ethiopia

and cow dung, to € 209 and € 9 for ponds with termite-mound soil, to € 226 and € 12 for ponds with clay soil, to € 511 and € 18 for ponds with cement, to € 619 and € 16 for ponds with geo-membrane plastic. The effective cost is the total cost per volume effectively utilized (effectively utilized volume is calculated from the product of the total storage volume and storage efficiency). Costs for materials were € 22–23 for average-sized ponds made with locally available materials and € 358 and € 548 for those made with, respectively, cement and geo-membrane. Labour costs were 86–90% (€ 133 to € 203) of the total cost for ponds reconstructed with locally available lining materials; significant cost reduction occurs where work is done by owner and neighbouring families.

## *3.2 Ndiva Systems in Tanzania*

### 3.2.1 Current Status

In 2011, the ndivas in the Makanya catchment, i.e. Manoo, Ndimka, Kavengele and Makanya, were still in operation. However, the Kavengele ndiva had not been well maintained resulting in high rates of water loss through leakage and seepage (Mahoo et al. 2012). Constraints were also reported for the Manoo ndiva, confirming the observations of Makurira et al. (2007). Most interventions to enhance water availability and increase agricultural production had been undertaken by external stakeholders targeting investments in irrigated agriculture rather than rainfed farming and ndiva systems. Attempts to enhance the capacity of water storage reservoirs and reduce conveyance losses had not been successful. Yet, in recent years, both technical assistance for ndiva improvement and farmer training on improved cultivation techniques have led to more effective use of water in fields.

The assessment study revealed four main reasons why the dam reservoirs, associated canals in the Makanya catchment suffer from capacity as well as social constraints (see also Critchley and Gowing 2012; Senkondo et al. 1999; SWMRG 2001a, b):

- Sizes of micro-dams are kept limited to avoid dam failure (both construction method and materials used hinder construction of larger dams);
- Water is wasted (due to seepage and evaporation) in both the reservoir and the unlined canals conveying water from its source to the reservoir and from the reservoir to the fields;
- Lack of financial resources impede dam construction and rehabilitation;
- Siltation occurs in water collection chambers and reservoirs due to poor management of catchment areas and water sources.

The payback period of a ndiva system is about two years, and the benefit-cost ratio 1.21. Whereas the initial investment cost is usually paid by local governments —through their District Agricultural Development Plans (DADPs)—and contributions from communities, the annual operations and monitoring are done by the beneficiary communities themselves.

### 3.2.2 Impact on Food Security and Livelihood

Agriculture plays a key role in meeting food needs among households in the Makanya catchment, directly through cultivation of food crops such as maize and beans and indirectly through cultivation of cash crops (e.g. *Lablab purpureus* or lablab-bean), whose profits are used to purchase food. Hence, lack of rain and erratic rainfall are perceived as the most constraining factors in achieving and maintaining food security as both livestock and crop production depend on rain. Adoption of ndiva systems can help households overcome such constraints and improve food production, yet, its effect on sustainable livelihood on a longer-term basis proved limited so far (Table 4).

**Table 4** Effects of ndiva system on crop yield, food security, livelihood and water allocation based on the perceptions of households surveyed in the Makanya catchment study, Tanzania

| Indicator | Effect |
|---|---|
| Yield | During times of scarce rainfall, households that have adopted ndiva systems enjoy significantly higher yields from their fields compared to those with fields depending on direct rainfall only; yet, women generally receive lower proportions of yield benefits compared to men, with men (husbands) often controlling their access to harvest; women benefitted primarily by deception, i.e. by theft of small harvest portions to be given to a friend to store for later consumption, or for sale to acquire cash to meet household or personal non-food needs |
| Food security | Households that have adopted ndiva systems experience improved food security and well-being "from year to year", except for those with distant fields mostly out of reach of the ndiva system and hence affected by fluctuating yields due to changes in rainfall |
| Livelihood | Despite the adoption of ndiva systems, households experience limited contributions to sustainable livelihoods on a more long-term basis as the unreliability of rainfall and associated variation in annual crop yields make it difficult for households to plan ahead and properly budget the use of their harvest; for women, benefits are, in general, lower due to the lack of ability to sell agricultural produce when in need, with casual labour (e.g. on sisal plantations) and savings groups contributing more significantly towards livelihood outcomes than agriculture |
| Water allocation | There is a high level of organization of water allocation: more or less all farmers within the ndiva system were given equal opportunities to receive water except for those with unlined canals and distant fields not reached by water from the canals during times of low rainfall |

### 3.2.3 Ndiva Improvement: The Lining of Conveyance Canals

The lining of conveyance canals entailed the construction of a stone pavement around an earth (unlined) canal (Fig. 5). The material costs were € 1613 (TZS 3,900,000) per 100 m lined canal. It took 17–20 days (by three skilled and three semi-skilled labourers for, respectively, € 3.30 and € 6.20 per person per day) to complete 100 m of lined canal. The lining of canals was investigated because it not only can minimize water losses and shorten water travel time but it also can save time for irrigation by allowing the release of a considerable amount of supplemental water within a short time span to grow crops. High distribution efficiency, with conveyance efficiency rising from 22 to 70% (Table 5), further implies a greater potential for yield increase and long-term sustainable livelihood among farmers with lined conveyance canals (Fig. 6), compared to those using unimproved systems or no ndiva systems. Moreover, relatively larger benefits can be expected for farmers with distant fields previously not reached by water conveyed through unlined canals from dam reservoirs. In order to support dissemination of these findings, the positive performance of lined canals was shared with district officers who incorporated the project findings into the District Agricultural Development Plans (DADPs), assuring ownership of the interventions by the beneficiary farmers (Kahimba et al. 2015).

**Fig. 5** Improved, lined irrigation canals to transfer water with minimum conveyance losses and shorter time from dam reservoir to field, Bangala, Tanzania. *Photographs* Sokoine University of Agriculture, Tanzania

**Table 5** Performance indicators measured for lined and unlined conveyance canals in the Makanya catchment, Same district (Kilimanjaro Region), northern Tanzania

| Indicator | Result |
|---|---|
| Conveyance efficiency[a] | As much as 70% of the water released from a micro-dam reached the end of a 400 m canal that had been lined, while this was only 22% for a 400 m unlined canal |
| Water travel time | Water running from micro-dam to fields using innovated canals reached its destination six times faster than before when unlined canals were used; a farmer with field along a lined canal had to wait for less than one second for the waterfront to reach his field (counted from the time the waterfront was one metre away); a farmer with field along an unlined canal had to wait more than four seconds |
| Flow velocity[b] | 1.46 m $s^{-1}$ for lined canal and 0.24 m $s^{-1}$ for unlined canal |
| Distribution efficiency[c] | Compared to unlined canals, the lined canals allowed farmers to irrigate larger field areas for a given time allocation and also fields located further away from the reservoir, while using the same amount of water stored in the dam reservoir |

[a]*Conveyance efficiency* [water received at field inlet ($m^3$)/Water released at micro-dam ($m^3$)] × 100%
[b]Measured over one-metre distance, starting when waterfront was at 1 m distance from field inlet
[c]Irrigated area per volume of water stored in dam reservoir per time unit

## 3.3 *Combinations of Mechanized Zaï, Grass Strips and Bunds in Burkina Faso*

### 3.3.1 Current Status

Whereas some of the WHTs tested in this research have been practised traditionally (e.g. earth bunds), others were introduced via external agents in the southern region, such as the stone lines and zaï pits at the Péni site. Intra-seasonal dry spells pose the

**Fig. 6** Maize growth performance in (left) lined canal-supplemented fields (water from dam reservoir) compared to (right) rainfed fields during Masika season in Bangalala village. *Photographs* Sokoine University of Agriculture, Tanzania

greatest risk to crop production and food security across all types of household at the study sites. Hence, farmers tended to adopt a variety of water management methods in their fields to capture rainwater, reduce runoff and encourage infiltration for increasing available crop water and overcome dry spells (e.g. vegetated bunds, zai pits). In some cases, however, when wet conditions prevail, farmers had to divert runoff away from their fields in order to prevent crop loss due to runoff and flooding.

The adoption of WHTs was not as widespread as expected based on the notion that intra-seasonal dry spells pose the greatest risk to crop production and food security. Reduction of crop risk provided by WHTs was not considered sufficient to warrant the technologies' adoption by farmers without first having secured access to a range of other agricultural assets (e.g. fertilizers, high-quality seed). Farmers with higher dependence on agriculture for income and better access to agricultural inputs adopted a wider range of WHTs across more fields compared to those with lower dependence on agriculture and more limited access to inputs (see also Boyd and Turton 2000; Barry et al. 2008).

### 3.3.2 Impact on Food Security and Livelihood

In terms of impacts, there was no evidence of farmers in the case study sites obtaining 100–200% increases in yield, as reported by FAO (2002, 2003). Similarly, there was no evidence of significant improvements in wealth or any other livelihood outcome across households using the water harvesting technologies. On the contrary, few households meet their food needs through crop production alone, even in average or good rainfall years when using WHTs; yet, the crop gains that did occur as a result of the WHTs contributed to food security. The latter was primarily in terms of increased quantity of food (i.e. calorific value), across all typologies of household, as WHTs were primarily used in conjunction with staple cereals (sorghum, millet and maize).

### 3.3.3 WHT Improvement and Impact on Soil Quality and Crop Yield

The improvement of the WHTs consisted of combining three or more different technologies ($WTH^+$) including water harvesting (mechanized zaï), bunding (earth and stone bunds), grass strips and fertilization. In general, the use of the WTHs in combination with (organic) fertilizers had a positive impact on soil quality; soil pH, organic matter, N, P and K contents increased after two years from the start of the on-farm experiment. In Boukou, P and K contents for the 0–10 cm and 10–20 cm soil horizons of plots combining water harvesting with fertilization reached about two times the total P and K, 96% of the available P and 58% of the available K contents of the control plot (Table 6). Soil organic matter contents also increased up to 70% compared to the control plot. In Péni, compost application to farms with grass strips and zaï or to farms with earth bunds and contour ploughing showed the highest increases in soil total P (i.e. between 48 and 86%) and available P (between 50 and 92% increase) for the 0–10 and 10–20-cm soil layers (Table 7). Soil N content showed a minimum of 50% increase and for OM and total K, minimum increases of, respectively, 33 and 30% were recorded. Mechanized zaï in combination with stone bunds and fertilizers gave a 250% increase in sorghum yield and mechanized zaï in combination with grass strips an 83% increase in maize yield as compared to the control.

### 3.3.4 Costs and Benefits of Water Harvesting, Fertilization and Bunding ($WTH^+$)

All combinations of WHTs tested by the on-farm experiments had a positive (economic) return to farmers, thus providing opportunities to enhance livelihood. At Péni, all farm plots resulted in positive financial margin with the exception of the control field which recorded a loss of F CFA 265 (€ 0.40; Table 8). Zaï pits in combination with grass strip and the use of compost were profitable on a minimum area of 1613 $m^2$ (0.16 ha). Each F CFA 100 invested in this field gained a production value of F CFA 120 with a profit margin of F CFA 20. At Boukou, all the experimental treatments were profitable on the plot size used in the study (2500 $m^2$ = 0.25 ha). The combination of "stone row + mechanized zaï + compost + NPK + urea" is the most profitable in sorghum cropping (Table 8). For this site, the technology is already profitable for an area of only 832 $m^2$ (Table 8). For both the centre and western regions, the use of adapted water harvesting technologies, in combination with soil fertility management, improved soil chemical properties, crop yields and farmers' incomes. To achieve these benefits in practice, a minimum investment is needed for WHT adaptation which,

**Table 6** Effect of WHTs on soil (0–20 cm) properties and sorghum yields at Boukou, centre zone of Burkina Faso

| Treatments[a] | BD ($g\ cm^{-3}$) | pH | $P_{tot}$ ($mg\ kg^{-1}$) | $P_{avail}$ ($mg\ kg^{-1}$) | $N_{tot}$ (%) | MO (%) | $K_{tot}$ ($mg\ kg^{-1}$) | $K_{avail}$ ($mg\ kg^{-1}$) | Grain yield ($kg\ ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| Control (T0) | 1.63 | 5.57 | 96.9 | 3.46 | 0.083 | 1.79 | 710 | 42.7 | 700 |
| CP + ZM + MO + EM (T1) | 1.61 | 5.82 | 141.9 | 3.66 | 0.096 | 1.80 | 2181 | 52.4 | 2034 |
| CP + ZM + Compost + EM (T2) | 1.55 | 5.64 | 229.8 | 6.84 | 0.146 | 2.68 | 1021 | 65.0 | 2159 |
| CP + ZM + MO (T3) | 1.69 | 6.00 | 152.8 | 5.02 | 0.139 | 2.94 | 1071 | 39.9 | 2680 |
| CP + ZM + Compost (T4) | 1.85 | 5.96 | 264.7 | 4.25 | 0.099 | 2.06 | 796 | 61.5 | 1956 |
| *P* values | <0.001 | 0.08 | <0.001 | 0.001 | <0.001 | <0.001 | 0.011 | 0.003 | <0.001 |
| LSD[b] | 0.11 | 0.41 | 62.0 | 1.58 | 0.022 | 0.52 | 873.4 | 13.64 | 1375.8 |

[a]Treatments include *CP* stone rows; *ZM* mechanized zaï; *MO* organic matter; *EM* mineral fertilizer; *ACN* earth bunds and contour ploughing; *BE* grass trip; *ZM* mechanized zaï

[b] Least significant difference test

**Table 7** Effect of WHTs on soil (0–20 cm) properties and maize yields at Péni, western zone of Burkina Faso

| Treatments[a] | BD (g $cm^{-3}$) | pH | $P_{tot}$ (mg $kg^{-1}$) | $P_{avail}$ (mg $kg^{-1}$) | $N_{tot}$ (%) | MO (%) | $K_{tot}$ (mg $kg^{-1}$) | $K_{avail}$ (mg $kg^{-1}$) | Grain yield (kg $ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| Control (T0) | 1.45 | 5.77 | 138.9 | 11.06 | 0.059 | 1.22 | 325.1 | 79.01 | 1826 |
| ACN + MO + EM (T1) | 1.55 | 5.66 | 148.5 | 13.51 | 0.086 | 1.626 | 436.3 | 61.65 | 2777 |
| ACN + Compost + EM (T2) | 1.47 | 6.16 | 252.9 | 19.12 | 0.095 | 1.845 | 487.1 | 58.97 | 2520 |
| BE + ZM + MO (T3) | 1.44 | 5.99 | 193.8 | 14.11 | 0.083 | 1.596 | 368.4 | 41.76 | 3114 |
| BE + ZM + Compost (T4) | 1.43 | 5.66 | 205.1 | 20.52 | 0.073 | 1.509 | 383.0 | 53.42 | 2917 |
| *P* values | 0.002 | 0.045 | 0.001 | 0.06 | <0.001 | <0.001 | 0.03 | 0.88 | 0.03 |
| LSD[b] | 0.07 | 0.32 | 57.76 | 7.42 | 0.012 | 0.29 | 111.25 | 86 | 1103 |

[a]Treatments include *ACN* earth bund and contour ploughing; *MO* organic matter; *EM* mineral fertilizer; *BE* grass strip; *ZM* mechanized zaï
[b]Least significant difference

**Table 8** Economic impact of water harvesting technologies at Péni and Boukou, Burkina Faso

| Treatments | Gross return (F CFA[a]) | Benefit (F CFA) | Benefit/ cost ratio | Profitability threshold ($m^2$) |
|---|---|---|---|---|
| *Péni* | | | | |
| 1. Zaï + grass strip + farmer OM[b] | 89,796 | 56.021 | 1.63 | 1507 |
| 2. Earth bund + farmer OM | 80,886 | 48.712 | 1.55 | 989 |
| 3. Earth bund + compost | 51,990 | 18.615 | 1.21 | 1605 |
| 5. Zaï + grass strip + compost | 54,050 | 19.175 | 1.20 | 1613 |
| 6. Control (no WHT) | 31,010 | −265 | 0.99 | 2522 |
| *Boukou* | | | | |
| 1. Control (stone row and no fertiliser) | 23,714 | 990 | 1.03 | 2397 |
| 2. Stone bund + mechanized Zaï + farmer OM + NPK + urea | 71,614 | 42.891 | 1.88 | 1003 |
| 3. Stone bund + mechanized Zaï + compost + NPK + urea | 89,874 | 59.963 | 2.16 | 832 |
| 4. Stone bund + mechanized Zaï + farmer OM | 49,219 | 21.499 | 1.48 | 1409 |
| 5. Stone bund + mechanized Zaï + compost | 65,164 | 35.254 | 1.94 | 1148 |

[a]€ 1 = CFA Franc (F CFA) 655.597 or 656
[b]farmer OM: organic fertilizer made by the farmer with his own skill

however, may form a barrier particularly to resource-poor farmers. Granting access to credits for agricultural inputs will help these farmers make the necessary improvements.

## 4 Discussion

The impact of the WHTs in Ethiopia, Tanzania and Burkina Faso proves to be below expectation, particularly with regard to food security and livelihood improvement. Although households using WHTs reported yield improvements, most families were unable to meet their (nutritional) food needs every year and experienced limited or no long-term effects on sustainable livelihood, using various coping strategies to deal with food and other related shortages. These findings support the findings of Mekdachi Studer and Liniger (2013) analysing 60 case studies of WHTs worldwide. The returns from WHTs proved to be too small for crop production alone to lift the poorest households out of poverty.

The WHTs tested on farms in Burkina Faso seem promising, with a 250% increase in sorghum yield for mechanized zaï in combination with stone bunds and fertilizers at the lower rainfall site and an 83% increase in maize yield for the mechanized zaï in combination with grass strips at the higher rainfall site.

The yield increase at the Péni site corresponds to the average yield increase of 80% reported by Bouma et al. (2016), based on the meta-analysis of 221 water harvesting field studies in semi-arid Africa and Asia. They found the relative largest impact of water harvesting on crop yields in low rainfall years. However, Gowing (2015) found for Burkinabe conditions that the probability of achieving increases in yield of even 50% or more is rather limited (let alone an increase of 250%), when accounting for rainfall-related crop risk based on longer-term rainfall records (50 years). The outcome of their quantitative risk analysis, extended with the Aquacrop simulation model applied for Burkinabe conditions (an agroclimatic zone with mean annual rainfall of 750 mm), showed an average yield increase of 25%. Moreover, the probability of achieving a yield increment of at least 50% was below 10%. These results are in line with the large standard deviation of 84%, and the several studies reporting limited yield increases, found in the WHT meta-analysis conducted by Bouma et al. (2016). The marginal reduction in rainfall-related crop risk that the use of WHTs can provide is unlikely to lead to high adoption by farmers unless it is seen as means of recovering unproductive land.

WHT adaptation and maintenance further need a minimum investment that most of farmers do not have. Although promising, the lining of household ponds and ndiva conveyance canals with appropriate materials needs to be considered when economically justified (see Bouma et al. 2016 for an economic analysis of WHTs). The same is true for the combination of WHTs tested in Burkina Faso where minimum investment may form a barrier particularly to resource-poor farmers. Incentive measures to support farmers are needed, including the provision of access to credits for agricultural production and access to inputs such as durable lining materials, improved seeds and fertilizers.

An important factor determining the extent to which benefits had been achieved is related to the degree of community involvement and the quality of external intervention provided during the WHT planning and implementation processes. In the case of household ponds in Ethiopia, community involvement was limited or inadequate. The latter explains why the intended beneficiaries were unable to develop a sense of ownership, and often the ponds were constructed in a suboptimal location. This is in line with Awulachew et al. (2005) who linked low performance of WHT in Ethiopia to flawed project design and lack of adequate community consultation during project planning. The ponds that were constructed as part of NGO programmes or by the households themselves proved better maintained than those constructed as part of government programmes. Participatory planning and design of the runoff ponds with due consideration of local circumstances and including a watershed approach are essential (Lasage and Verburg 2015). External intervention, where applied in a sustainable and participatory manner, remains crucial for the continued existence of WHTs not only in Ethiopia but also in Tanzania and Burkina Faso. In the latter country, the adoption and expansion of WHTs have been low outside of communities supported by external interventions (Morris and Barron 2014).

## 5 Conclusions

Rainfed systems of crop production pose a great challenge especially in the drought-stricken semi-arid and arid areas of sub-Saharan Africa. WHTs have the potential to harvest and store rain and runoff water for use at times when there is no rain, or for bridging dry spells through supplemental field irrigation during the wet season. Successes of WHTs noted through this research relate to the creation of an enabling (policy) environment (e.g. providing credit facilities to farmers, extension services and participatory technical support) and the promotion of WHT as a package ($WTH^+$), together with other agricultural inputs (e.g. improved seeds and fertilizer), adapted to the local environmental, social and economic context within which they are implemented.

Failures are primarily related to the high level of unpredictability in risk reduction combined with the range of asset-related constraints that farmers experience. The most vulnerable farmers will not develop to an agricultural self-sufficiency level by solely investing in water harvesting systems, as their position is dependent on a multitude of factors (e.g. nature of asset endowment, activities engaged in and market access), of which water availability is only one. On the other hand, improving water harvesting systems for farm households that are not considered to be the most vulnerable in their region can be beneficial for enhancing their livelihood situation, especially when the additional yield can be sold on a market. There is a risk that improvement is mainly through the quantity rather than the quality of food available. WHTs are often primarily implemented to increase the production of cash crops, with the earned income being used to improve the quality of diet and other livelihood needs (e.g. medical care, schooling). Also, food security and poverty are both multi-dimensional concepts, suggesting increased crop production does not necessarily equate directly to increased food security or reduced poverty. More research on the role of WHTs in nutrition-sensitive agriculture is recommended.

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# Roads: Instruments for Rainwater Harvesting, Food Security and Climate Resilience in Arid and Semi-arid Areas

**Frank van Steenbergen, Kifle Woldearegay, Marta Agujetas Perez, Kebede Manjur and Mohammed Abdullah Al-Abyadh**

**Abstract** With an investment of 7–10 billion USD in sub-Saharan Africa, the development of roads is a major factor in the change of landscapes and the drainage patterns. Thus, roads often act as conveyance systems, but the impact is often negative, leading to erosion, waterlogging and flooding. These impacts come down hardest on the more vulnerable and least resilient, such as poor female-headed households. Yet these negative effects can be turned around and roads can be made into instruments for rainwater harvesting, food security and climate resilience. In this regard, there is a variety of techniques that can be used—ranging from simple interventions in the area surrounding the roads to modified designs of road bodies. What drives the transformation of roads is a change in governance too—better coordination between road builders and water resource and agricultural departments and closer interaction with roadside communities. This chapter provides evidence from Yemen and Tigray region in Ethiopia, where road water harvesting has systematically been introduced in all districts since 2014. The chapter describes the process of promoting road water harvesting, the techniques used, the potential of road water harvesting to increase resilience and the hydrological and socio-economic effects.

**Keywords** Road water harvesting · Erosion · Ethiopia · Yemen

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# 1 Introduction

Roads have a major impact on the landscapes immediately surrounding them—determining the movement of water, sediment, dust and others (Forman et al. 2003). Roads have an important impact on runoff because they often act as either an embankment or a conveyance system, bringing major changes to the natural hydrology (Forman et al. 2003). These changes often have negative impacts: roads cause local floods and waterlogging along the way, whereas the more concentrated discharge from drains and culverts causes erosion and sedimentation (Garcia-Landarte et al. 2014; Demenge et al. 2015). This undermines the resilience of roadside communities, who lose crops or property or suffer health effects from road dust (Greening 2011).

However, this negative aspect can be reversed if roads are systematically used as instruments for rainwater harvesting (Nissen-Petersen 2006). Thus, road harvesting can generate substantial positive impacts: more secure water supply, better soil moisture, reduced erosion and respite from harmful damage (Demenge et al. 2015). In addition, rainwater harvesting leads to better returns to land and labour, and a higher ability of people, households and communities to deal with and prosper regardless of shocks and stresses (Dile et al. 2013). With the investment in roads in many countries exceeding that of any other programme, this is a large opportunity to improve the productive environment and increase the resilience of the population in the vicinity of the road.

This chapter describes the process of promoting road water harvesting to increase resilience. It first describes the techniques and approaches to road water harvesting (Sect. 2). It then zooms in on the experience of Tigray region in Ethiopia (Sect. 3) where the collection of water from roads has been introduced as a systematic feature in the water conservation and moisture management campaigns since 2014. Section 4 describes the link between road water harvesting and resilience, providing examples from Tigray. The chapter concludes with a suggestion on how to systematically build-up resilience by connecting road development and water resources management in sub-Saharan Africa.

# 2 Methodology

## 2.1 Study Area

The region of Tigray in Northern Ethiopia and large areas in Yemen are subject to rainfall variability, land degradation and undernutrition. Thus, rainfall is unpredictable and unreliable with a higher concentration between June and August when about 70% of the total runoff is obtained in Tigray (Abebe et al. 2012). However, not all is negative. The Northern Ethiopia highlands in Tigray are greener than at any time in the last 145 years (Nyssen et al. 2014). Since 1980s, soil and water conservation (SWC) and water harvesting techniques have been widely implemented to tackle land degradation and foster development by reducing surface runoff and enhancing infiltration, sediment deposition and vegetation growth (Nyssen et al. 2014). There are a large range of options to collect water with roads and join the SWC efforts in the region such as diverting water from culverts, using the springs that are opened up with road construction or reusing excavation pits as storage reservoirs.

One such area was the upgraded route Freweign-Hawzien-Abreha Weatsbeha-Wukro in Tigray, Northern Ethiopia. This road section of 64-km-length crosses three woredas (districts): Saesie Tsaeda Emba (woreda center is Freweign town), Hawzien woreda (woreda center is Hawzien town) and Klite Awlaelo woreda (woreda center is Wukro town) (Fig. 1). The surveyed routes include both feeder roads and asphalt.

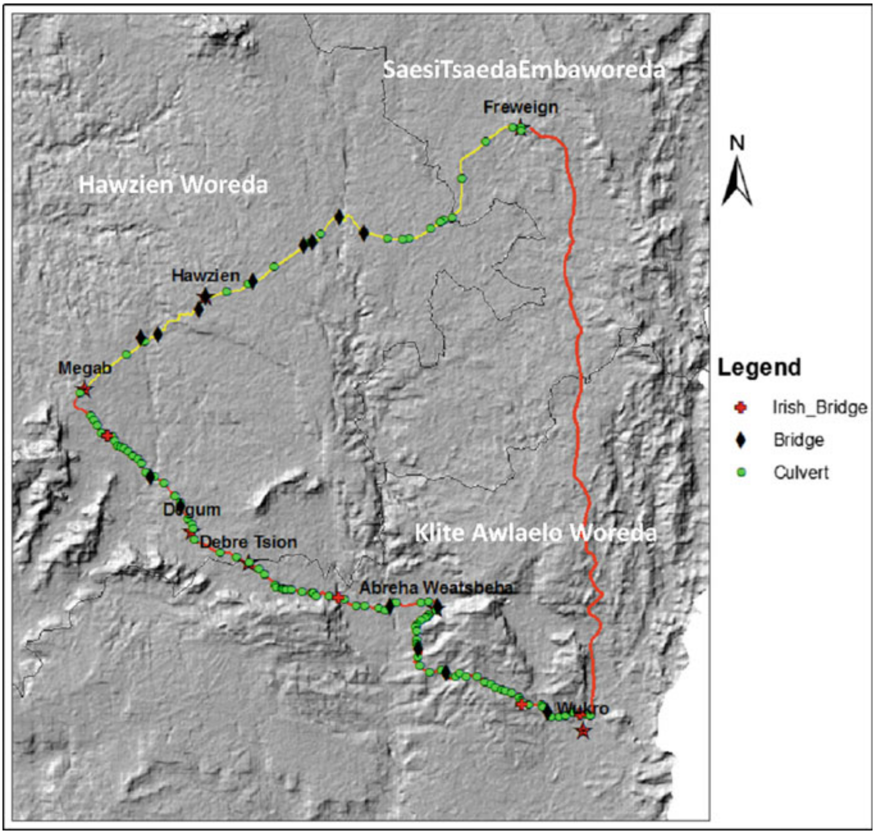


**Fig. 1** Location map of the study area in Tigray, Northern Ethiopia (Wukro-Megab is a gravel road planned to be upgraded into asphalt; Megab-Freweign is recently upgraded into asphalt; Wukro-Freweign is an asphalt road which is part of the main highway in Northern Ethiopia)

### 2.2 Methods

If water from roads is not handled properly, the result is erosion, flooding, and siltation/sedimentation due to the disturbance of natural drainage systems. Such was the case along the Freweign-Hawzien-AbrehaWeatsbeha-Wukro road section as well. A detailed assessment was done of: locations of culverts, Irish bridges and bridges; areas affected by gully erosion; sites affected by waterlogging and flooding; and sites where efforts have been made to implement different soil and water conservation measures along a 5-km-radius from the main route. The survey was carried out in the period of July to September 2013.

Moreover, a socio-economic study was conducted in Saesi Tsaeda Emba district of Northern Ethiopia along the newly constructed Freweign-Hawzen highway. Data were collected from document reviews and randomly selected respondents representing all social groups of the community (such as women, men and wealth groups better off, middle class poor) along the road and water harvesting structures. Both participatory and structured surveys were used to collect data. The participatory rural appraisal (PRA) tools included: participatory mapping, transect walks, wealth ranking matrix, gender matrix, seasonal calendars and interviews with leaders and officials at the *tabia, woreda* and regional level. Participants of the PRA included men and women, representatives of different wealth groups, members of households that practice irrigated and rainfed agriculture and individuals particularly affected by the road. Overall, data were collected from 129 household semi-structured survey and 15 interactive discussions. Finally, data were analysed using descriptive statistics, triangulation and content analytical tools.

## 3 Results

### 3.1 Collecting Water from Roads and Road Catchments

Tropical drylands are exposed to significant rainfall variability which leads to recurrent periods of water deficiency and make them particularly vulnerable to droughts, floods and other extreme events (Falkenmark and Rockstrom 2008). At the same time, drylands cover 42% of the world's population on 40% of the world's land area and host two billion people (United Nations 2011). Moreover, poverty and undernutrition are to great extent concentrated in tropical drylands, which are also suffering from water and land degradation. Thus, resilience against droughts and dry spells is fundamental for water and food security in these areas (Falkenmark and Rockstrom 2008).

Farming systems in sub-Saharan Africa drylands consume less than 10% of the seasonal rainfall available, whereas the remaining rainfall constitutes massive water losses (Falkenmark and Rockstrom 2008). At the same time, millions of cubic metres are being drained through the road surface and drainage systems every rainy season. There is an estimated 5.55 million km of roads in sub-Saharan Africa (Kubbinga 2012). Of this, 2.36 million km are in drylands, respectively, in rangelands (1.57 million km) and in cultivated areas (0.80 million km) (Kubbinga 2012). If these water losses could be put to productive use, sustainable productivity levels of farming systems could be multiplied by four (Falkenmark and Rockstrom 2008).

Road water harvesting potential depends on several landscape characteristics. Table 1 presents drainage characteristics, erosion susceptibility and road water harvesting potential for different landscapes.

Rainwater harvesting has repeatedly been suggested as a prime option for a sustainable water management strategy to increase agricultural production (Rosegrant et al. 2002; Reij et al. 2009). Water harvesting systems result in higher farm productivity (Dile et al. 2013) increasing farm productivity by 78% on average (Bouma et al. 2016). Unlocking the potential of roads and road-related infrastructure in order to harvest the massive amount of water being currently lost will help to

**Table 1** Roads versus landscape

| | Drainage characteristics | Erosion susceptibility | Water harvesting potential |
|---|---|---|---|
| Lowland and plateau | Higher difficulty to drain but depends on soil characteristics. Road embankment can interfere with subsurface and surface flows, especially when no clearly developed drainage pattern | Waterlogging and undermining of road pavements can be a problem. Side drains and embankment stability depends on design standards | Borrow pits, rolling dips, tanks, cross drainage to infiltration areas, hand-dug wells, manually drilled shallow boreholes and flood water spreading. Borrow pits can serve as dug out ponds with natural seepage |
| Mountain-valley | Easier to drain at toeslopes and moderate vertical profile slope. However, ridge top and valley bottom are harder to drain | Depending on roughness of surface, soil characteristics and slope. Deep, portable soils and steep slopes are prone to trigger erosion issues | Several rainwater harvesting techniques can be applied: spring capture, recharge of borrow pits, retention ponds, water cisterns and tanks, side drains/culverts leading sheet water flows to nearby fields and terraces, canals from culverts to fields, spillways from road surface to farms |

*Source* Garcia-Landarte et al. 2014

improve the livelihoods of rural dwellers now suffering from water scarcity, degradation and malnutrition.

There is a large range of options to collect water with roads (Table 2), most of them falling within two main approaches: “adapting to the road” and “adjusting the road”. The first approach involves utilizing directly or indirectly the runoff and water flows generated by roads. The latter relates to optimizing road design for water harvesting and erosion control. Making roads climate and waterproof are often costly and less roads can be built. Instead, road development should be optimized to lead to food security and climate resilience.

### *3.2 Adapting to the Road: Using Runoff and Water Flows Generated by Roads*

There are several interventions that can be implemented to nearby already constructed roads and appurtenant infrastructure. A technique that can be easily implemented is spreading water directly to farmlands from road surfaces by using stone bunds or digging shallow canals. Alternatively, water can also be diverted to

**Table 2** Overview of road water harvesting techniques and their benefits

| Approach | Techniques | Benefits |
|---|---|---|
| Adapting to the road | Spreading water from road surface and culverts | Groundwater recharge<br>Soil moisture increase<br>Erosion/flooding control |
| | Harvesting water from culverts, side drains and depressions (borrow pits, small reservoirs, infiltration ponds, infiltration trenches and swales) | Groundwater recharge<br>Water storage<br>Soil moisture increase<br>Erosion/flooding control<br>Pollution control by naturally filtering |
| | Gully plugging | Soil moisture increase<br>Erosion control<br>Groundwater recharge |
| | Spring capture | Reliable source of clean water (unless naturally polluted) |
| Adjusting the road | Fords combined with sand dams | Groundwater recharge<br>Water storage<br>Flood control |
| | Carefully planning road alignment and culvert location | Groundwater recharge<br>Water storage<br>Erosion/flooding control |
| | Permeable road foundations | Groundwater recharge<br>Pollution control by filtering |

structures for surface storage or groundwater recharge. Below is a brief explanation of what can be done with runoff and water flows generated by roads.

#### 3.2.1 Spreading Water from Road Surface and Culverts into Farmland

During rain events, road surfaces generate a large amount of runoff. In addition, a vast amount of water coming from the upper catchment passes through culverts and side drains (Fig. 2). This water can be easily utilized by diverting it to nearby farmlands for supplemental irrigation. Roadside farmers in Tigray region have reported to have an increase of up to 50% in yields as compared to farmers far from the road.

#### 3.2.2 Harvesting Water from Culverts, Side Drains and Depressions

Road drainage structures can be used not only for cross drainage but also to feed as the water source for borrow pits and storage ponds or for enhanced recharge areas such as infiltration ponds, swales and infiltrations pits.

(a) Converted borrow pits

Borrow pits are the result of the excavations made to extract materials for road construction. Borrow pits are often left open and located nearby roads, which offer an opportunity for water harvesting. They can be used as storage reservoirs for rainwater for instance connecting them with culverts and other cross-drainage structures through a canal. However, some measures are needed to improve the

**Fig. 2** Water spreading from road surface to farmlands in Tigray, Ethiopia. *Photograph* Kifle Woldearegay

design, safety and accessibility. These measures include technical considerations such as improving the geometry to facilitate access and increase capacity, compress the base and sides to reduce permeability and construction of well for water extraction to allow filtration and improve water quality (AFCAP 2011).

(b) Small reservoirs for water storage

Runoff can also be channelled for storage in small reservoirs (Nissen-Petersen 2006). This water can be later utilized by roadside communities for small-scale irrigation purposes and for livestock watering. There are two main types of ponds that can be built, namely embankment ponds and excavated ponds (USDA 1997). Embankment ponds are built by constructing an embankment or dam across a waterway where the land is depressed enough to allow for water storage. Excavated ponds are built by digging a pit or dug out in an almost flat area. Since they require more labour and machinery, excavated ponds are mostly used where only a small supply of water is needed. Dug outs are particularly useful in dry areas where evaporation losses are high and water is scarce, since they can be built to expose a minimum water surface. A combination of both types of ponds can be built in gently to moderately sloping areas where the capacity is achieved both by excavating and by building a dam or embankment.

(c) Infiltration ponds

Infiltration ponds are designed to capture and retain runoff, letting it to infiltrate for groundwater recharge (Desta et al. 2005). They are advantageous in places where runoff might be polluted (such as next to highways) and where shallow wells and hand-pumps are viable. According to Massman and Allen (2003), the first step to design infiltration ponds is to estimate the volume of runoff that must be infiltrated. Secondly, a trial geometry must be defined. The next step is to estimate the infiltration rate by multiplying gradient and hydraulic conductivity and finally conduct post-design evaluations.

(d) Infiltration trenches

Infiltration trenches protect the fields from upcoming runoff and let the water infiltrate in the soil (Desta et al. 2005) (Fig. 3). They increase the soil moisture of the adjacent farmlands, which in turn has a positive impact in yields.

### 3.2.3 Gully Plugging for Recharge

When road drainage is not managed properly it can lead to the formation of gullies (Nyssen et al. 2002). Gully plugs are used to rehabilitate gullies and retain the sediments that would be otherwise washed away. Gully plugs are structural barriers that obstruct the concentrated runoff inside gullies and ravines (Knoop et al. 2012) (Fig. 4). They are often temporary structures and are built to favour the establishment of a permanent soil cover and to effectively conserve soil and water.

**Fig. 3** Infiltration trenches along an asphalt road in Amhara Region, Ethiopia. *Photograph* Marta Agujetas

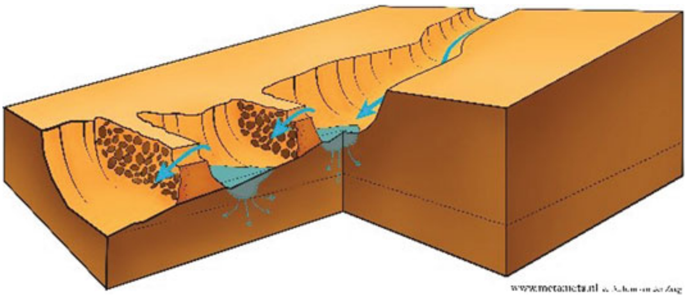

**Fig. 4** Gully plug for groundwater recharge. *Source* MetaMeta

Gully plugs can have an enormous beneficial effect on the soil moisture of adjacent lands as well as shallow groundwater tables (Knoop et al. 2012). In fact, in an area where gullies are present, soil moisture will be drained and shallow groundwater will drop to the depth of the drainage line of the gully (Knoop et al. 2012).

### 3.2.4 Spring Capture

In mountainous areas, the excavation for road building purposes can open springs in mountain aquifers. These newly opened springs can damage cut slopes and erode land (Garcia-Landarte et al. 2014). Capturing newly opened springs in storage reservoirs that are adequately dimensioned and have spillways facilities is a safe way to make available a source of water that otherwise would be lost. When the spring water is not of good quality, it can be diverted to infiltration structures such as ponds or swales.

## *3.3 Adjusting the Road: Improving Road Design for Multiple Functions*

Improved and integrated road designs can increase groundwater recharge and retention while controlling water-related damage (Garcia-Landarte et al. 2014). Optimized designs can particularly improve water storage in the vicinity of the road, in open ponds and cisterns, but also as secure soil moisture and as shallow groundwater.

### 3.3.1 Fords Combined with Sand Dams

Low-volume rural road river crossings such as fords or non-vented drifts can be used for seasonal rivers to retain and store water in the upstream side while protecting the road embankment (Neal 2012). They can also be used for flood water spreading and riverbed stabilization. When carefully designed and located, fords can also act as sand dams (van Steenbergen and Tuinhof 2010) (Fig. 5). Sand dams that incorporate a ford are a low-cost alternative to culverts and offer a wide array of benefits including groundwater recharge, downstream flow risk reduction and provide reliable water supply in drylands (Neal 2012). However, they can only be built on seasonal rivers with sufficient sandy sediment. The design of spillway should be done in a way that does not cause the river to spread or divert. To prevent the river damaging the road foundation, a concrete apron or gabions extending for 2 m from the base is recommended downstream of the crossing (Neal 2012).

### 3.3.2 Carefully Planning Road Alignment and Culvert Location

An ideal road follows the existing natural topography. However, this is not often the case as roads end up acting as dams or embankments and changing local water flows (van Steenbergen and Tuinhof 2010). This problem could be reversed by planning road alignment and culvert location in such a way that they maximize water harvesting and recharge (Garcia-Landarte et al. 2014). Road location within the catchment determines water harvesting opportunities from roads. Road alignment and its drainage structures can be purposely designed to feed water storage and recharge facilities such as ponds and borrow pits. They should also be planned in a way that the risk of erosion is minimal and at the same time the potential for

**Fig. 5** Road crossing doubling up as a sand dam in Makueni, Kenya. *Photograph* MetaMeta

water harvesting is the highest. For instance, culverts often concentrate runoff in specific spots and often cause gullies and erosion. By studying the hydrology of an area, culverts could be strategically placed to distribute road drainage and prevent erosion.

### 3.3.3 Permeable Road Foundations

Especially on tarmac roads, the use of permeable substrata would allow percolation or infiltration of runoff through the road surface into the soil. Besides reducing storm water runoff and flooding and replenishing groundwater, it also poses a solution to road-related water quality issues since the water is naturally filtered by the soil underneath. So far, this technology is mostly used in parking lots, sidewalks, low-traffic roads, fire lanes and emergency access roads. However, the potential to harvest storm water is huge due to the expanding road infrastructure in sub-Saharan Africa.

## *3.4 Case Study in Tigray Region, Ethiopia*

Triggered by a research project, the Tigray Bureau of Agriculture and Rural Development introduced in 2014 several road water harvesting technologies in all of its districts as part of the watershed program. Hundreds of road water harvesting structures were built, all indigenous solution to the areas where they were implemented. Monitoring established significant impact in terms of reduced fear of flooding, increased moisture (30–50%), higher shallow groundwater tables (in metres) and higher yields. There is scope to do a lot more—not only in systematically using the water runoff from road catchments but also by even adjusting the design of the roads themselves or consideration of road water harvesting options in design standards. The approaches used to promote road water harvesting in Tigray included: (a) assessment of issues on water and roads along selected routes in Tigray, (b) understanding the perception of the communities on road development versus water-related challenges, (c) designing methods of involving stakeholders to take the lead in the implementation of the interventions, (d) implementing different water harvesting options, and (e) monitoring the effects of the interventions in selected/representative sites where there was prior data (baseline data).

The survey result revealed that several problems have been created due to water from roads including erosion in downstream areas and roadsides and siltation/sedimentation of downstream, upstream and side drainage areas. Waterlogging and damage on dwelling houses and on water harvesting systems (groundwater wells and ponds) were also observed in the study area. In the 64 km of roads, there were 159 problems spots—close to 3 per km.

Until the year 2013/2014, there was no systematic approach for road water harvesting in Tigray, as elsewhere in Ethiopia. There were, however, sporadic practices implemented as part of the soil and water conservation efforts. Since the year 2013/2014, efforts were made to introduce road water harvesting in a more systematic manner. Main practices of water harvesting from roads implemented in the study area thus far were financed by the government (particularly the Tigray Bureau of Agriculture and Rural Development) and implemented during a mass mobilization campaign of June–July 2014 when farmers provided labour days for watershed moisture improvement. The main technologies and approaches implemented are presented below:

- **Use of ponds/pits to harvest water from roads**: Since 2010, ponds have been constructed to collect water from any source including roadside drainages. Along the study route, five ponds have been constructed for surface water storage and groundwater recharge. It is common to have water from a culvert channelled into a properly design pond. The storage of rainwater can provide an extra source of water for irrigation, helping to improve the food security in the area.
- **Channelling water from bridges, culverts and roadsides into series of deep trenches**: In seven locations along the route, water from culverts and roadside drainages was channelled into deep trenches (Fig. 6). Deep trenches are often used to control runoff and enhance groundwater recharge processes (Desta et al. 2005). Measurement of the in situ moisture of the soils around the trenches shows an increase in moisture content of the soil (up to over 100%) as compared to the previous year of the same season (Fig. 7).


**Fig. 6** Water from a culvert is channelled into a deep trenches in Megab area, Tigray, Ethiopia. Hand-dug well downstream of these trenches is used for monitoring. *Photograph* MetaMeta

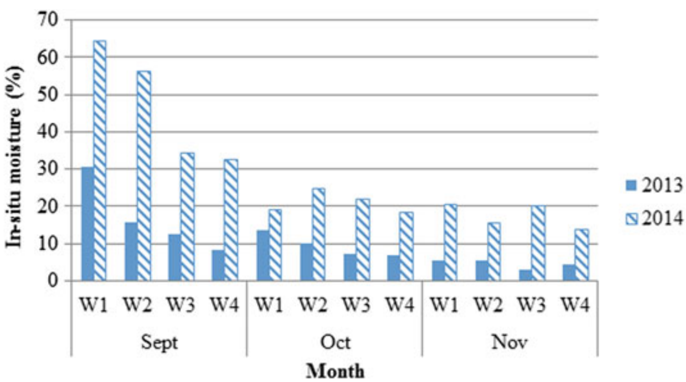


**Fig. 7** In situ moisture distribution in soils before and after the construction of deep trenches at downstream of culverts in Megab area, Tigray, Ethiopia. Construction of the deep trench was done on June 2014. Monitoring was done for the period September–November for both years (2013 and 2014). (W1 = Week one; W2 = Week two; W3 = Week three and W4 = Week four)

- **Channelling water from culverts and roadsides into farm lands**: Diverting runoff (from roadsides and culverts) into farmlands (Fig. 8) is one of the technologies implemented in Tigray. The purpose of this structure is to enhance the availability of water for crop production. In situ soil moisture measurement results (Fig. 9) shows that as compared to previous year of the same season, the soil moisture of the soil has improved after the interventions (by up to 100%).

- **Channelling water from bridges, culverts, and roadsides into check dams:** Though check dam construction is a common water harvesting and gully treatment technique in Tigray, linking water from roads with check dams is a new development. With the purpose of storing water from culvert, bridges and roadsides and for the purpose of enhancing groundwater recharge, check dams

**Fig. 8** Diverting roadside runoff into farmlands as part of moisture conservation in Kiken area (along Mekelle-Wukro road), Tigray, Ethiopia. *Source* Kifle Woldearegay

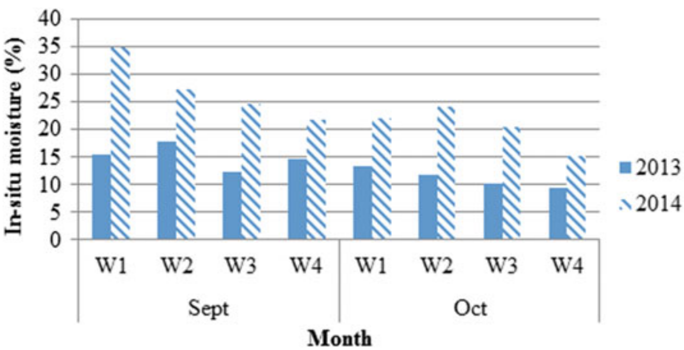


**Fig. 9** In situ moisture distribution in soils before and after the construction of structures that divert runoff from culverts into farmlands along the Mekelle-Wukro road (Kiken), Tigray, Ethiopia. Construction of the diversion structures was done on May–June 2014. Monitoring was done for the period September–October for both years (2013 and 2014). (W1 = Week one; W2 = Week two; W3 = Week three and W4 = Week four)


**Fig. 10** Channelling water from a culvert into a check dam is enhancing groundwater in Selekleka area, Tigray, Ethiopia. *Photograph* Kifle Woldearegay

are constructed in many parts of Tigray (e.g., Fig. 10). Results of the groundwater level measurement show that due to the construction of the check dam, the shallow well which used to have no yield in the dry season before the intervention has become very productive even in the dry season (Fig. 11).

- **Shallow groundwater development upstream of Irish bridges**: Along the study area, four Irish bridges and fords were identified. These structures can have multiple functions. The first obvious one is to allow road traffic to cross the dry river bed. The fords can, however, also double up as a sand dam, trapping coarse sediment behind them and creating small local aquifers that can store and retain water (Neal 2012).
- **Conversion of borrow pits to water storage and recharge structures**: In some areas, catchment runoff was concentrated in a large cross-drainage structure with three culverts. This new structure created a constant threat and fear of flooding, and in one event, 46 houses were destroyed. To resolve this problem, it was proposed to channel the runoff through a 3-km-long canal to the river, but this would require considerable land acquisition. A more cost-effective solution was used when a 250-m-long canal was excavated to the borrow pit which was converted 5000 $m^3$ storage and recharge pond. This has resulted in an increase in groundwater level downstream of the pond (Fig. 12) coupled with a reduction of flooding in downstream areas.

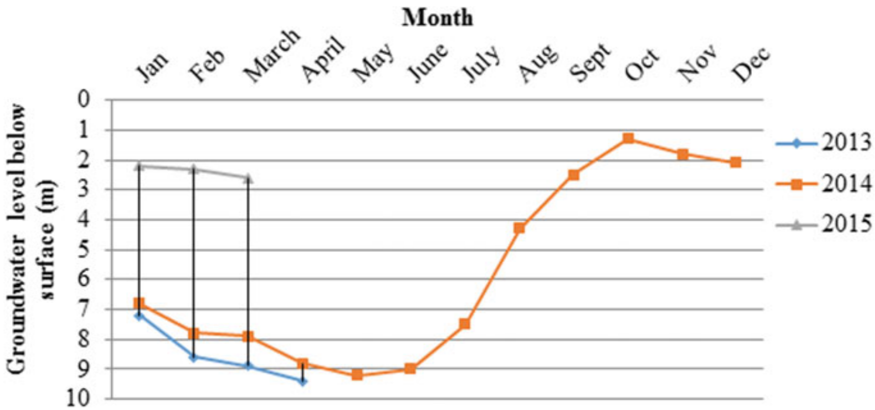


**Fig. 11** Groundwater fluctuation in Selekleka area, Tigray, Ethiopia (at downstream of a check dam which was constructed in the period January–May, 2014). The check dam is designed to store water from a box culvert. New groundwater is created at downstream of the box culvert, and the construction of the check dam has enhanced groundwater level in the area

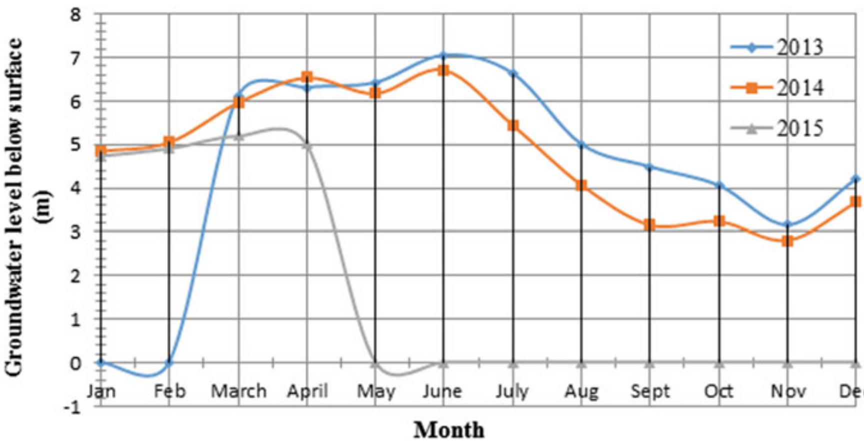


**Fig. 12** Groundwater fluctuation in Freweign area, Tigray, Ethiopia. The well is located at downstream of a borrow pit converted into a water storage pond on July 2014. Monitoring was done for the whole period March 2013 to April 2015

## *3.5 Case Study in Yemen*

Yemen has a long and well-established tradition in water harvesting, with a wide variety of technologies showing huge creativity in retaining rain water (Al-wadaey and Bamatraf 2010). Road water harvesting has been successfully introduced in several locations along the national road network and rural feeder roads. In most cases, the technologies have been implemented by farmers themselves.

Other initiatives have been carried out by road engineers and contractors such as the use of borrow pits as recharge ponds or using the road embankment as a dam.

Below there is a description of the road water harvesting practices documented so far:

- **Roofed and open cisterns or tanks collecting water from the side drains**: this technology has been observed along roads in Yemen. Some of the cisterns use sedimentation basin. Figure 13 presents an example of a roofed cistern fed by the side drain. The side drain is partially closed by stones to divert the water to the cistern. The stones are used to block the first runoff after a long dry period as it may be contaminated.
- **Tree planting along roads**: almond, coffee, qat and Ficus trees are being planted to collect road runoff using half-moon stone bunds. They are found in the road embankment, shoulders or in new arable lands near the road to benefit from the diverted flood water from road surface and shoulders.
- **Diverting water directly from culverts to fields**: road water is diverted by using conveyance pipes from the culvert outlet to the farm. Figure 14 shows a conveyance polyethylene pipe with a plastic filter at the pipe intake and a small stone collection basin at the culvert outlet.
- **Diverting road surface water either by using temporary humps or by constructing a catch basin**: temporary humps are built with stones prior rain events to divert road runoff to adjacent farmland or water harvesting structures. Another method is to collect water from roadside drainage using concrete bricks and a bar mesh to trap sediments. The harvested water is then conveyed under the road through a pipe (Fig. 15).


**Fig. 13** Roofed roadside cisterns collecting road runoff in Yemen. *Photograph* Mohammed Abdullah Al-Abyadh


**Fig. 14** Water from a culvert is gathered in a collection basin and transported through a polyethylene pipe. *Photograph* Mohammed Abdullah Al-Abyadh

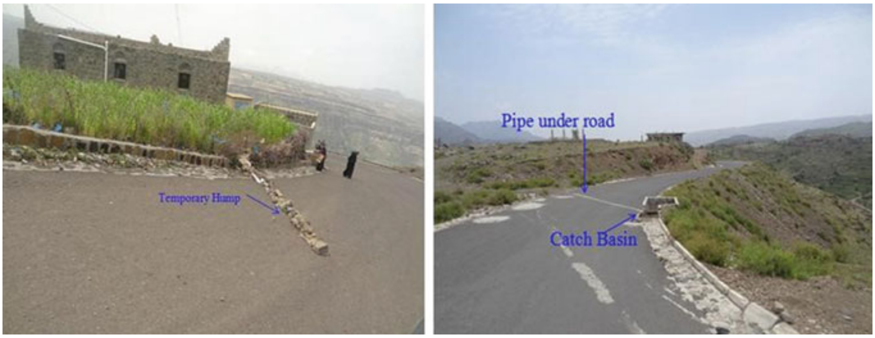


**Fig. 15** Temporary hump diverting water from road surface to farmland and catch basin collecting road runoff and transporting it under the road. *Photograph* Mohammed Abdullah Al-Abyadh

# 4 Discussion

## *4.1 Enhancing the Resilience of Roadside Communities*

A paradigm shift is happening from conventional resource management that aims to reduce variation and increase predictability to resilience thinking or adaptive management as a way of dealing with uncertainty and shocks (Folke 2006). Resilience relates to the capacity to adapt, recover, develop and remain flexible (Falkenmark and Rockstrom 2008). In this section, the authors argue that road water harvesting provides a strategy to build adaptive capacity against shocks and extreme events by providing an extra source of water during dry spells, increasing soil moisture and reducing risk of floods. In addition, water can be stored in ponds, shallow wells and small dams and can be used for livestock or a second cash crop during the dry season. This will provide extra sources of income and therefore increasing farmers' resilience against adversities.

There is a need for a paradigm shift in the design and construction of roads in the following areas:

1. Design roads that have multiple benefits by considering the interest of local communities.
2. Design innovative cost-effective and sustainable infrastructures that are resilient to climate change.
3. Develop national, regional and even global design approaches that consider the multifunctionality and climate resilience of road infrastructures.

Rather than undertaking costly endeavours to protect roads against climate change, new concepts should be developed to integrate roads in the landscape and add to overall resilience. For instance, climate change adaptation costs for road infrastructure in Europe are estimated to be 314–560 million €/year (Nemry and Demirel 2012). There is a need to optimize the multifunctionality of roads to increase resilience. Apart from being used for water harvesting, roads can be also used for sand harvesting, wildlife management and flood control in delta areas (Forman et al. 2003). The main bottlenecks hindering the implementation of this approach are the current practice in road engineering and the lack of coordination between different agencies. Most road engineering guidelines concentrate on how to evacuate water from the road to avoid damage. Harvesting water from roads and their associated infrastructure is not considered as an option in road design. In addition, roads, water and agriculture departments in Ethiopia and elsewhere often work independently and collaborations are rare despite their interdependence. However, to systematically implement road water harvesting, a solid collaboration between government agencies dealing with road development, agriculture and environment needs to be fostered.

Though relatively forgotten and underutilized, capturing water from roadside drains, culverts or along road embankments is in many cases the easiest way to capture runoff. The network of roads is fine-grained and in many areas fast increasing. The ability to better retain water will help farmers to tide over drought periods and increase their capacity to deal with shocks. Results from research in Tigray showed that supplementary irrigation with water from the road increased crop yields by mitigating intra-seasonal dry spells in the month of August, which is the crop maturity period. Moreover, implementing water harvesting systems reduce the risks of crop failure, making farmers more willing to invest in fertilizers and other agricultural inputs (Dile et al. 2013), which will increase even more the crop yields.

## 4.2 Impacts on Food Security and Poverty Alleviation

Water resilience in agriculture aims at safeguarding water availability under periods of shocks, such as persistent droughts (Falkenmark and Rockstrom 2008). At present, current road building practice reduces resilience of roadside population. Thus, in 100 km of roads there may be 13–25 problem spots—from flooding, waterlogging, erosion or uncontrolled sand deposition. Several studies have found that a reduction in the quality of natural resources often leads to a loss of resilience (Kelly et al. 2015).

This is the case in our study area. Out of 129 respondents, 53.5% of them perceived an increase in water runoff during peak rainy season due to the waterway created along the roads. Thus, many farmers faced flooding, waterlogging and siltation of fields, making land less productive and more difficult to cultivate which in turn resulted in loss of arable land and soil infertility (Table 3).

In the case study site, land holding size was 0.79 ha and crop productivity was 1422.21 kg/ha.

In terms of economic loss, on average about 0.07 ha (11%) of land and 69.23 kg (9%) of yield of crop was lost due to road-induced runoff (Table 4).

**Table 3** Impact of road runoff on rainfed farming, living house and runoff intensity

| Affected attributes | | Frequency | % |
|---|---|---|---|
| Rainfed farm | Flooded | 67 | 51.9 |
| | Silted | 67 | 51.9 |
| | Eroded | 39 | 30.2 |
| Grazing land | Flooded | 58 | 45 |
| | Silted | 56 | 43.4 |
| | Eroded | 20 | 15.5 |
| House | Flooded | 32 | 24.8 |
| Runoff | Increased | 69 | 53.5 |

**Table 4** Impact of road runoff on agriculture

| | Minimum | Maximum | Mean | Std. deviation |
|---|---|---|---|---|
| Farm size | 0.25 | 1.5 | 0.79 | 0.28 |
| Farm land loss (ha) | 0 | 0.25 | 0.07 | 0.09 |
| Annual yield (kg) | 200 | 5400 | 1422.20 | 1002.03 |
| Total yield loss (kg) | 0 | 400 | 69.26 | 91.25 |
| Percentage of farm land loss | 0 | 100 | 10.88 | 15.70 |
| Percentage of yield loss | 0 | 72.73 | 8.95 | 13.05 |
| Monetary loss (ETB) | 0 | 3200 | 589.76 | 738.39 |

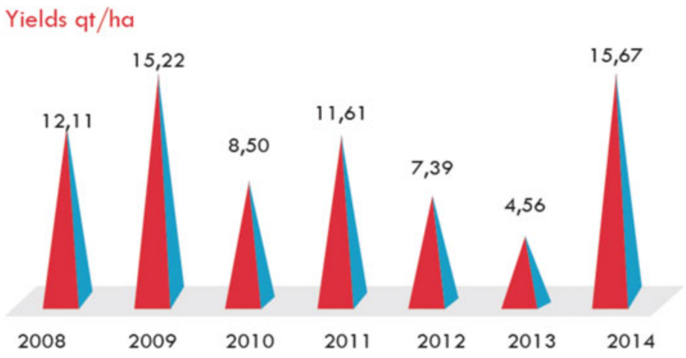


**Fig. 16** Yield (in quintal) per hectares in Sinqata before and just after the road construction in 2013

However, road runoff can also have positive impacts if managed wisely. Figure 16 shows that the implementation of road water harvesting structures restored productivity in 2014 even though this was a relatively low-rainfall year.

Figure 16 presents the yield trend of the study area, seven years. From 2008 to 2009, there was slight yield increment due to availability of rainfall while in 2010 there was a decline due to low rainfall. Suddenly, during road construction period (2011–2013), as there was flooding and erosion, crop yield was reduced to 4.56 qt/ha. In response to this decrease on yields, from 2014 the water was diverted to a nearby borrow pit to retain road runoff and increase steady percolation of water. The yields were re-established and the maximum crop yield reached 15.8 qt/ha. There is hence a clear link between making use of roads for water and increased productivity and resilience. Some estimations determine that every 10% increase in yields in Africa leads to a 7% reduction in poverty (Pretty et al. 2011).

## 5 Conclusions

Road development is not only one of the major investments worldwide but also one of the practices that cause changes in runoff patterns in landscapes. Roads act as conveyance systems or as barriers and can cause water-related problems, if not managed. For road water to be managed and to minimize all the negative effects, there is a need to move towards the development of proper standards and approaches in the design and construction of roads.

The main reason for the link between roads and water not taking place at present is governance. At present, road development is largely single objective. The sole purpose of building roads is that of creating transport corridors. In many countries, there is no cooperation with other stakeholders for instance in agriculture or water resources nor a culture or practice of consulting roadside communities. Though indicated in the design guidelines to take care of environmental concerns, in practice, roads remain among the major causes of environmental problems. The designs and guidelines for road development do not consider the possible beneficial use of water along roads, but are primarily concerned with safeguarding roads from water damage. Among road builders, there is generally little consideration of the impact of roads on the environment immediately surrounding them, though indicated in their design manuals and standards.

To move from ‘roads that cause harm’ to ‘roads for resilience’ requires changes in the technology used, appreciation of the different contexts in which roads are developed, the introduction of consultative processes and importantly changes in governance. Governance needs to be multi-stakeholder and recognize the reduction of risk and the distribution of access to benefits. It requires sensitivity of the impact of different road water harvesting options for male and female livelihoods, better linkages to male/female roles in different socio-economic contexts, ensuring female representation in local consultation processes and consideration of special measures to engage and support female-headed households in better road water harvesting and other opportunities created by roads for resilience.

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# Part II
# Case Studies and Field Experiences

# Fostering the Use of Rainwater for Off-Season Small-Scale Irrigation in Arid and Semi-arid Areas of Ethiopia

**Belay Simane, Taffa Tulu, Amare Lantideru and Desalegn Dawit**

**Abstract** The rainwater harvesting (RWH) techniques most commonly practised in Ethiopia today are run-off irrigation (run-off farming), flood spreading (spate irrigation), in situ water harvesting (terracing, ridges, micro-basins, etc.) and roof water harvesting. While there are abundant examples and practical experiences of rainwater harvesting experience in Ethiopia, the momentum gained so far on the expansion and application of modern RWH for irrigation is below the country's potential and needs. The major identified bottlenecks for rapid adoption of RWH for agricultural purpose in Ethiopia are high cost of construction of structures compared to income accrued as a result of the adoption of the technology; lack of trust (awareness) on the contribution of the technology; incompatibility of the technology with local farming system; lack of appropriate training how to construct, use and maintain structures; improper planning, implementation and promotion of the technology by development agents/experts; and lack of commitment to promote the technology compared with other agricultural extension activities. Large numbers of RWH and SSI technologies are already introduced in the country. Their efficiency, effectiveness, acceptance and impacts on the livelihood, however, vary considerably from place to place. An enabling environment and governmental support are essential for spreading the concept and implementation of rainwater harvesting systems on a large scale. Mainstreaming in policy agendas, awareness raising, capacity building and technical exchange are all important for enhancing the use of rainwater harvesting systems. Furthermore, land use and land ownership have to be taken into account, as well as suitable technology and storage medium. As some systems require high maintenance costs, it is important that rainwater harvesting options are made attractive for farmers themselves to invest in these technologies.

**Keywords** Climate change · Ex situ water harvesting · In situ water harvesting Ethiopia

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## 1 Introduction

Agricultural production in Ethiopia, where more than 90% are delivered by subsistence farmers, depends on unreliable rainfall. Over the next 50 years, Ethiopia would experience increasingly erratic weather, with higher rainfall, and a temperature rise of at least 3 °C (McSweneey et al. 2010). Ethiopia's low level of economic development combined with its heavy dependence on a climate-sensitive agricultural sector and its high population growth rate makes the country particularly vulnerable to climate change (Alemneh 2003; Simane et al. 2012). This could result in prolonged droughts and floods, which would affect crop yields as well as increase existing tension around resource use. Deforestation, accelerated soil erosion and land degradation are also predicted to affect the future food security of the country (Simane et al. 2016). As a result, there is an urgent need for appropriate investments in water storage to increase agricultural productivity and build the resilience of communities, by ensuring that farmers have options for adjusting to climate change. Rainwater harvesting is one effective water technology for adaptation to increased variability in water supply and rainfall.

Ethiopia is endowed with huge potential of rainwater harvesting and irrigable land (Tulu 2015a, b). Government of Ethiopia has developed a 15-year strategy for household irrigation in 2011 (MoA 2011). The strategy gives emphasis in the use of household technologies for irrigation including rainwater harvesting technologies. It also emphatically declared that the Ethiopian Agriculture has to be transformed from rain-fed to irrigation and from subsistence level to commercial.

Modern rainwater harvesting (RWH) and SSI practices in the country, such as small earth dams, rock catchment dams, subsurface dams and ponds, have recent history (Tulu 2008, 2015a, b; Seleshi et al. 2009), which was started in mid-1970s as response to the then catastrophic drought. In recent years, large numbers of these technologies were already introduced in the country. Their efficiency, effectiveness, acceptance and impacts on the livelihood, however, vary considerably from place to place. The storages have also different shapes and sizes.

The promotion and application of rainwater harvesting techniques as alternative interventions to address water scarcity in Ethiopia were started through government-initiated soil and water conservation programmes. It was started as a response to the 1971–74 droughts with the introduction of food-for-work (FFW) programmes, which were intended to generate employment opportunities to the people affected by the drought. Large portion of Ethiopia (a) has clear seasonal differentiation into wet and dry months; (b) experiences strong inter-annual and seasonal variation of rainfall; (c) is suffering from climate change; and (d) has heterogeneous landscape, which causes differences in rainfall and temperature pattern. This provides great potential for future RWH and SSI undertakings. In many parts of Ethiopia, traditional rainwater harvesting and small-scale irrigation have been practised for centuries (Tulu 2015a, b). Currently, both traditional and introduced small-scale irrigation technologies are expanding in many parts of the country in the face of rainfall variability, on the one hand, and due to the favourable policy environment of the government, which encourages farmers to transform their agriculture from purely rain-fed to irrigation-based farming, on the other hand. However, the degree of acceptance and implementation of these technologies varies from region to region.

This chapter is a summary of the current status of rainwater harvesting applications in Ethiopia. The specific objectives are to address the existing rainwater harvesting technologies that are practised in Ethiopia, evaluate the perception of experts on RWH best practices in the country and assess adoption of RWH and SSI by the smallholder farmers.

## 2 Methodology

The study is based on an extensive literature review and in-depth key informant interviews with practitioners in the field of RWHI in Ethiopia. Field visits to various infrastructures and focus group discussions with the community were also done. Literature review includes different institutions, proceedings regarding the RWH and SSI undertakings in the country and papers published regarding the experiences of RWH and SSI. The analytical framework, which was used to assess experts' opinion on best practices of RWH and SSI, was the framework suggested by Aderson and Burton (2009). Questionnaires were sent to 50 experts to get their perception and opinions on several aspects of RWH/SSI and particularly requested to evaluate implementation of them from the framework of best practice measurement perspective.

## 3 Results and Discussion

### *3.1 Rainwater Harvesting Technologies in Ethiopia*

As part of integrated agricultural water management, in situ and ex situ rainwater harvesting systems are used as an adaptation mechanism for climate change and to improve the livelihood of the small-scale farmers in Ethiopia. The in situ systems, which enhance soil infiltration and water-holding capacity, have dominated over ex situ (storage) schemes in Ethiopia until recently. Despite the additional costs involved in storage schemes, the recent trend shows there is a relatively high degree of adoption. Interest in rainwater collection has steadily increased in both regions where they have been used traditionally and those where the technology was previously unknown. The overall weighted rank of RWH technologies considering technical, economic, social and environmental feasibility criteria puts on-farm ponds and shallow groundwater technologies as the most feasible options followed by in situ RWH and rooftop catchment (Table 1). Earthen small dams and artificial groundwater recharge technologies are ranked as fifth options.

In situ rainwater harvesting systems are based on changing soil and water management techniques, with the aim to improve infiltration, water-holding capacity and fertility of the soil, and to counter soil erosion. It is basically related to sustainable land management practices. In Ethiopia, soil and water conservation began in the late 1970s as a response to excessive land degradation in the rugged eastern, central and northern part of the country. Since 1990s in an attempt of correcting the negative impact of top-down approach and physical-biased SWC activity, participatory integrated watershed development instituted and adopted by the government and NGOs/CSO in all regions of the country (e.g. Lakew et al. 2005). Soil and water conservation measures include terracing, pitting, conservation tillage practices, commonly implemented to control soil erosion by increasing soil infiltration. In general, the in situ systems, which enhance soil infiltration and water-holding capacity, have dominated over storage schemes in Ethiopia until recently.

The ex situ rainwater harvesting technologies are systems which have rainwater harvesting capture areas external to the point of water storage. Technologies of ex situ systems include wells, dams, ponds or cisterns where water can be abstracted easily for multiple uses including for irrigation or for domestic, public and commercial uses through centralized or decentralized distribution systems. These systems can achieve even higher outcomes if supplemented by measures of sustainable land management, conservation agriculture, slopping land management such as terraces, gully rehabilitation and crop rotation for increasing organic matter content in the soil. Experiences of development projects in Ethiopia suggest that sustainable

**Table 1** Overall weighted rank of RWH technologies considering technical, economic, social and environmental feasibility

| RWH technology | Weighted rank | | | | Overall weighted rank |
|---|---|---|---|---|---|
| | Technical | Economic | Social | Environmental | |
| On-farm ponds | 1 | 3 | 3* | 3 | 1* |
| Earthen small dam | 7 | 8 | 2 | 1 | 4** |
| Sand dam | 9 | 8 | 8 | 6 | 7 |
| Subsurface dam | 8 | 7 | 7 | 5 | 6 |
| Rock catchment | 5 | 4 | 5 | 7 | 5 |
| Rooftop catchment | 2 | 5 | 4 | 2* | 3 |
| In situ RWH | 3 | 2 | 3* | 4 | 2 |
| Shallow groundwater | 6 | 1 | 1 | 2* | 1* |
| Artificial groundwater recharge | 4 | 6 | 6 | 2* | 4** |

The technologies with similar asterisks are ranked equal and locally adapted rainwater harvesting systems can contribute to food security and adaptation to climate change, and improve the livelihood of farmers (Simane 2016).

RWH through construction of ponds that either were initiated by individual households/farmers or were supported by NGOs and government was among major water harvesting technologies for irrigation of high-value crops (e.g. vegetables and fruit trees) and/or for supplementary irrigation for annual crops in Ethiopia. This activity reached climax in the country in the years 2003–2005. Ponds are different in size and shape (trapezoidal, semi-hemispherical, spherical, circular, dome shape, bottle shape, rectangular, square). The household-level ponds have an average capacity of 60 $m^3$. It is often constructed at backyard for vegetable cultivation. It is also used for crop production for supplemental irrigation when constructed close to the farm plot. Community-scale ponds are also commonly constructed mainly by the support of different NGOs (Tulu 2001, 2002, 2008, 2015a, b; Seleshi et al. 2009). Some of them lined by concrete, while the majority lined with geomembrane plastic. Reports indicate big number of them failed. For example, Leul (2009) reported that from 2002 to 2005 more than 858,503 rainwater harvesting structures (private ponds, community ponds, hand-dug wells, spring development) were constructed in Amhara, Oromia, Tigray and SNNP regional states of which about 380,575 (44%) were functioning by 2006. Despite such huge failures, there are very successful farmers who improved their production and their livelihood.

Like other water harvesting technologies, sand dam and underground water harvesting systems also have long history. Particularly in North Africa, this technology is as old as 2000 years. In Ethiopia, sand dam construction was dated to 1974 in eastern part of the country. The specific places where it started are around Dire Dawa (Adada, Ejaneni, Melka Belina, Gende Bira, Melka Jeldu, etc.) and Gursum area (Seleshi et al. 2009). These areas are semi-arid where agro-pastoralism and pastoralism are the major economic activities. Although pastoralists have their own indigenous water harvesting and management systems, water is a critical problem for their livestock and domestic use. Sand dam is considered an alternative technology for storing rainwater in the dryland pastoralis areas.

### *3.2 RWH and SSI Best Practices*

Perceived best practices observed in the last few decades while implementing RWH for agricultural activities in Ethiopia are presented in Table 2. Those specific indicators scoped by experts from each domain are: ‘availability of unsophisticated and easy to implement technologies’ from technical domain; the behaviour of the community towards ‘working together’ and ‘helping each other’ from social domain; existence of ‘demand’ and ‘good price’ for agricultural products from economic domain; ‘political support for agriculture sector and RWH’ from institution/policy domain; and existence of ‘conducive natural environment for RWH’ and current ‘natural resource conservation’ activities from environment

**Table 2** Experts' perceived best practices of RWH in Ethiopia ($n$ = 28)

| Domain of best practices | Subindicators of major domains | Response ($n$ = 28) | |
|---|---|---|---|
| | | Number | % |
| Which technical best practices and/or potentials exist on RWH? | Adequate experiences since the 1970s | 6 | 21.4 |
| | Functioning system | 9 | 32.1 |
| | Variety of designs | 8 | 28.6 |
| | Technically equipped and trained human power | 6 | 21.4 |
| | Unsophisticated and easy to implement technologies | 14 | 50.0 |
| | others/ | 2 | 7.1 |
| Which social best practices and/or potentials exist on RWH? | Cohesiveness | 3 | 10.7 |
| | Work together | 16 | 57.1 |
| | Help each other | 6 | 21.4 |
| | Limited conflict | 9 | 32.1 |
| | Others | 0 | 0.0 |
| Which economic best practices and/or potentials exist on RWH? | Communities can and are meeting MOM costs | 5 | 17.9 |
| | Available demand for agricultural production | 16 | 57.1 |
| | Accessible market at reasonable cost | 4 | 14.3 |
| | Good price for produce | 10 | 35.7 |
| | Availability of raw material for construction | 10 | 35.7 |
| | Others | 1 | 3.6 |
| Which institutional best practices and/or potentials exist on RWH? | Adequate legislation | | |
| | Political support for conservation agricultural | 18 | 64.3 |
| | Political support for RWH | 13 | 46.4 |
| | Functioning system of governance | 8 | 28.6 |
| | Functioning system of education | 2 | 7.1 |
| | Functioning knowledgeable and extension system | 4 | 14.3 |
| | Skilled Management, Operation and Maintenance | 3 | 10.7 |
| | Others | 2 | 7.1 |

(continued)

**Table 2** (continued)

| Domain of best practices | Subindicators of major domains | Response (*n* = 28) | |
|---|---|---|---|
| | | Number | % |
| Which environmental best practices and/or potentials exist on RWH? | Favourable physical environment | 17 | 60.7 |
| | Combating natural resource degradation | 17 | 60.7 |
| | Limited run-off and pollution of land, water for agric. | 5 | 17.9 |
| | Favourable health environment | 4 | 14.3 |
| | Others | 0 | 0.0 |

domain suggested by majority of experts as best practices to expand the RWH activities further in the future.

Case studies conducted at different parts of the country (e.g. Luel 2009; Nijhof et al. 2010) showed mixed results on the success, acceptability, effectiveness and efficiency of RWH that aimed towards enhancing food security of smallholder farmers. Diverse challenges and drivers were mentioned for such diverse responses.

The best technical practices regarding small-scale irrigation in Ethiopia include existence of varied and already tested designs of small-scale irrigation technologies that could be implemented in the different agro-ecologies. The experiences are not only success but also failures. The latter is equally important with the success stories in the area of implementation of SSI to draw lesson not to repeat the previous mistakes. Social best practices include the tradition of working together and helping each other are the two practices regarded as best from the social criteria in which 46 and 36% of respondents expressed the view. Existing demand for agricultural products is the major economic best practice and opportunity that exists for wide application of SSI. The existence of ‘political support for agriculture’ is identified as best institutional criteria. The current widespread activities to combat land degradation are important environmental best practices identified.

### 3.3 Barriers to Adoption of RWH and SSI by the Smallholder Farmers

Investment in RWH and irrigation, particularly in small-scale and household-level irrigation, has been identified as a core strategy in Ethiopia to reduce the strength of the link between agricultural production from rainfall and climate risk to improve crop production (Hagos et al. 2009a, b). RWH and SSI also require the use of

**Table 3** Experts' view on constraints of wider adoption for RWH and SSI in Ethiopia

| Constraint | Rank |
|---|---|
| Lack of appropriate training on construction and maintenance | 1 |
| Lack of commitment to promote it compared to other agricultural extension activities | 2 |
| Improper planning, implementation, promotion | 3 |
| High cost of construction compared to benefits | 4 |
| Incompatibility of technology with local farming system | 5 |
| Lack of trust to the technology (lack of awareness) | 6 |
| Absence of enough and appropriate equipment | 7 |
| Absence of clear regulation on water use among uses | 8 |
| Uncertainty of tenure of the structures | 9 |

modern inputs (such as, fertilizers and improved seeds), which further enhance agricultural productivity (MoFED 2006; World Bank 2006).

According to the survey result, the perceived rate of farmer's adoption of RWH for agricultural activities and SSI has increased steadily since 1990s and is expected to increase as adaptation strategy to climate change. However, experts' opinions revealed some pessimism in many of the issues and identified different challenges (Table 3). The major reason is mainly due to the hasty implementation of technologies and poor planning when implemented in a kind of campaign approach. Many of the implementations were not supported by research and demonstration.

The challenges ranged from policy-related issues to design of specific technologies. Those identified challenges and constraints in the order of their importance are: lack of or inadequacy of baseline studies for proper planning and decision making, lack of data and information on potentials of different areas for the development of water resources; poor technology choice; low yields of completed systems; unclear property rights of the facilities; too small landholdings for bringing impact on the livelihood; conflicts in water use and use rights; marketing, market access and market linkages; dependency syndrome of the some sections of the community in case where structures are constructed by NGOs; institutional arrangements and instability that manages RWH and SSI activities at different administrative tier of the country; lack of training to handle technologies; lack of extension services; lack of start-up capital or access to credit to initiate venture; poor linkage between research and extension in the area of irrigation water management. Regarding knowledge gaps, researchers identified the following constraints: faulty design; lack of knowledge on use of modern irrigation technology; poor water management; poor land management; poor input utilization; poor management capacity; lack of information and database and lack of post-harvest technology and management. In addition, the following are mentioned in several occasions: poor awareness of the technology; poor implementation procedures (use of only standard design which lacks flexibility according to the conditions; problems related to site selection; poor construction management; shortage of water to be harvested and stored; water lifting problems; shallow depth of irrigation water application; poor crop selection and cropping pattern problems with time and method of irrigation and limited experience in irrigation extension; maintenance related (tearing of plastic sheets, silt up of structures); environmental related (where some storages become breeding ground for malaria, hazard to human and animals, and stinging water).

Despite the existence and availability of large number of RWH and SSI technologies in the country, their efficiency, effectiveness, acceptance and impacts on the livelihood, however, vary considerably from place to place. The study of Wondimkun and Tefera (2006) in Amhara regional state showed that about 22% of the structures were found to be functional, 70% not functional and the rest was destroyed. Harvested water has been used for different purposes: 35.6% for irrigation only, 31.4% for other purposes (water supply, cleaning and construction) and 33% for both purposes.

Regarding the RWH, experts seem uncertain on the trend and continuity of it. It is only less than half of them that have the opinion on the issue. In the period 2000–2006, RWH, particularly ponds of different shapes, were constructed in almost all parts of the country in a top-down campaign approach in all districts of the country. As a result, several ten thousands of structures were constructed. For example, with regard to the future situation, experts indicated optimistic view for both RWH and SSI for agricultural purposes. Still, they indicated emphasis on the necessity of enhanced awareness and better training on the application of those technologies. The optimistic view of experts is supported by the government strategy for the period 2012–2025, which indicated the absolute necessity of promoting agriculture supported by irrigation.

## 4 Conclusions and Recommendations

Ethiopia has rapidly expanded in situ and ex situ rainwater harvesting (RWH) interventions to curb the threat of recurring drought incidences and rainfall variability due to climate change. Ponds of different size and shape are the most frequently constructed water storages that collect run-off from ground catchments. Flooding and furrow were the most common methods of irrigation used. However, quite large numbers of those structures constructed are currently malfunctioning. Inappropriate technology choice, design, operation, maintenance and other socio-economic and institutional reasons identified causative factors for such large failure.

Many of the implementations were not supported by research and demonstration. Challenges ranging from policy-related issues to design of specific technology were identified. There are also knowledge gaps and constraints on design; use of modern irrigation technology; water management; land management; information on database; and on post harvest technology and management. The awareness of the community on the technologies; implementation procedures; and environmental impacts are poor.

There are, however, considerable changes in recent years in the use of family drips at household level for water-use efficiency supported by NGOs, GoE that are promoting RWH and SSI. This calls for researchers to develop site-specific, cost-effective, socially acceptable and robust structures and planning and implementation procedures.

Although several failures are registered, equally there are brighter spots where farmers' production and livelihood are greatly improved. Those farmers worked relentlessly to make the technology productive. Analysing factors of failures and success are believed to be very important to rectify failure on the one hand and to upscale success. In terms of types, quite large number of RWH designs and types introduced in different parts of the country. However, which type is more appropriate, economical and acceptable by the community and which is appropriate from physical geographic criteria perspective detailed studies are needed.

Regarding the potential of RWHI, literature and previous studies confirmed that immense potential exists in Ethiopia. The annual amount of rainfall in the largest portion of the country generates excess run-off in the rainy months that can be stored to be used during the dry months. The topographic gradient can be taken a potential for appropriate ground catchment that it makes conveyance construction relatively easy just to collect the water and store it in smaller and medium storage facilities. Regarding the future prospect, the government is planning to expand SSI. This calls for researchers to develop site-specific, cost-effective, socially acceptable and robust structures and planning and implementation procedures. Doing things as usual cannot be taken as alternative. The policy framework should also be checked.

The main constraints of rainwater harvesting for small-scale irrigation are lack or inadequacy of baseline studies; poor technology choice; low yields; property rights; too small landholdings; conflicts in water use and use rights; marketing and market access; dependency syndrome; institutional arrangements and instability; lack of training to handle technologies; lack of extension services; lack of start-up capital or access to credit to initiate venture; and poor linkage between research and extension in the area of small-scale irrigation.

Based on the empirical evidences on the ground, the following three recommendations are made:

- Coordination of RWHI efforts by different stakeholders: efforts in RWHI are currently fragmented. NGOs, government departments and research institutions are doing their own interventions with none or little cooperation among themselves.
- Policy and guidelines for rainwater harvesting at household-level and small-scale irrigation: policy on RWHI mainly focuses on large and complex infrastructure but does not provide guidelines for technologies applied at lower levels such as rainwater harvesting at household-level and small-scale irrigation.
- Capacity building for development workers and farmers: extension workers are often not adequately trained on RWHI.

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# Fostering the Use of Rainwater for Off-Season Small-Scale Irrigation in Arid and Semi-arid Areas of Kenya

**Nicholas Oguge and Francis Oremo**

**Abstract** Water scarcity is a constraint to rainfed agriculture in tropical arid and semi-arid environments. This situation is likely to be exacerbated by climate change. Further, sub-Saharan Africa is expected to experience increased consumption of food, energy and water resources due to rapidly growing economies and urban populations. This calls for innovative and appropriate technologies to support production systems amid the changing climate. Collection, storage and use of rainwater for off-season irrigation, if combined with climate-smart agriculture, have the potential to improve food security and income for smallholder farmers. Replication, scaling-up and transfer of integrated rainwater harvesting (RWH) irrigation management systems require a multidimensional assessment of existing technologies and their use. This study sets out to assess and map best practices in RWH irrigation systems in dryland agro-ecosystems in Kenya. We used both primary and secondary sources in our evaluation. Primary data was based on key informant interviews of institutions and practitioners, and stakeholder workshops in RWH. Secondary sources included journals, technical reports and other relevant publications. Our study identified adoption of place-specific rainwater harvesting systems. These included in situ, micro- and macro-catchment technologies. While the in situ and micro-catchment systems included soil conservation measures, macro-catchment systems were run-off-based. Our finding shows that arid and semi-arid areas of Kenya have high potential for climate resilient food production if RWH irrigation technologies are adopted and scaled up, hence the need for policies that would promote adoption of context-specific rainwater harvesting technologies for different climatic, bio-physical, socio-economic and cultural conditions. This will enhance adaptive capacities of smallholder farmers and reduce their vulnerabilities to climate change while increasing food production to meet growing demand in the country with a view to contributing to sustainable development.

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**Keywords** Rainwater harvesting · Mapping · Best practices · Adoption
Dryland agro-ecosystems

# 1 Introduction

## *1.1 Background*

Kenya's population is currently estimated at 46,790,758 and growing at a rate of 1.81% (Index Mundi 2016). The urban population stands at 25.6% with the rate of urbanization being 4.34%. While it is estimated that over 21% (10 million people) of the population are food insecure (Food Security Portal 2016), the population growth trajectory and accompanying urbanization rate would suggest a projected increase in food demand. That calls for strategies to increase food production, currently inhibited by among others, frequent droughts (Republic of Kenya 2013). Given that over 80% of the population derive their livelihoods mainly from agricultural related activities, it would be prudent to develop strategies that would enhance adaptive capacity, strengthen resilience and reduce vulnerability of the smallholder agricultural system to climate change.

Water scarcity during crop growing season is a major drawback to small-scale agriculture in Kenyan arid and semi-arid (ASAL) environments. In ASAL areas, such scarcity is more related to high intensity and short duration of rainfall, with large spatial and temporal variability, rather than to cumulative annual and seasonal rainfall (Falkenmark and Rockström 2004; Malesu et al. 2012). Irregular patterns in precipitation result in high risk of drought and dry spells during crop growing season, leading to unpredictable and depressed crop yields, perennial food shortages and conflicts over use and access to limited water supplies (Ngigi et al. 2014). This situation is aggravated by the impacts of climate change with drought as a prime natural disaster in Kenya having been experienced six times in the last 30 years (Republic of Kenya 2015). Each of these events caused severe crop and livestock losses, famine and population displacement in the country.

Although arid and semi-arid areas are at the frontiers of economic water scarcity in Kenya, the potential of rainwater harvesting is enormous and remains untapped. In these areas, agriculture could be transformed through conservation of soil moisture in situ or by harvesting surface run-off for supplemental irrigation to bridge dry spells during crop growing season (Mutabazi et al. 2005; Mati 2007; Malesu et al. 2012). Therefore, meeting current and future food demands in arid and semi-arid areas will require the development and adoption of innovative water harvesting and storage technologies together with the introduction of climate-smart agricultural practices. Appropriate water management systems would include soil moisture conservation technologies (e.g. bunds and trenches) and on-farm storage structures (e.g. farm ponds).

The ASAL regions of Kenya constitute over 80% of the landmass and cannot reliably support rainfed agriculture unless supplemented with water harvesting and storage technologies (Malesu et al. 2012). Agricultural policies in Kenya are focused largely on large-scale irrigation development using blue water withdrawn from large water bodies including dams, rivers and lakes. Yet, this option is becoming increasingly difficult to sustain. Historical engineering's focus on blue water has led to the undervaluation of green water as an important factor of production (Hoekstra et al. 2011). Out of an estimated irrigation potential of 1.39 million ha, only 539,000 ha can be developed with available water resources (National Water Master Plan 1992). The rest (800,000 ha) would require annual water storage of 25 billion $m^3$. Currently, about 10% of irrigation potential has been exploited, which can explain the periodic food insecurity in the country (Onchoke 2014).

In crop production systems, rainwater harvesting refers to techniques of inducing, collecting, storing and conserving soil moisture or surface run-off for agricultural production (ACE 2015). Rainwater harvesting systems fall into two broad categories: in situ and ex situ depending on the source of water collected and storage point (Hatibu and Mahoo 2000). In situ rainwater harvesting technologies include practices that increase soil moisture conservation in the soil profile (Hatibu and Mahoo 2000; Malesu et al. 2006), i.e. use of green water for production. This approach aims at maximizing infiltration and minimizing surface run-off to achieve higher crop yields in places where soil moisture deficit is a constraint. Ex situ rainwater harvesting technologies, on the other hand, collect surface run-off from external catchments and store it either in the root zone (soil profile) or in the storage structure (earth dam, water pan, farm pond, underground tanks) for use during the dry spell (Hatibu and Mahoo 2000; Malesu et al. 2012).

In situ, RWH systems are more common in sub-Saharan Africa (SSA) than storage systems for supplemental irrigation (Critchley 1999). This is explained by long history of application of ethno-engineering practices by African cultivators under widely varying climatic conditions (Reij 1990). These practices are grounded in detailed knowledge of local environments and include a wide range of techniques such as crop rotation, mixed cropping, application of manure, terrace building, pitting systems and drainage ditches (Reij 1990). Nevertheless, rainwater harvesting for supplemental irrigation is gaining traction in the region (Kihara 2002). Under this system, surface run-off from small catchments (1–2 ha) or adjacent road run-off is collected and stored in manually and/or mechanically dug farm ponds of 50–1000 $m^3$ storage capacities. Hence, increased investment in rainwater harvesting will be a key factor in climate resilience agriculture particularly in arid and semi-arid regions.

Despite the importance of smallholder agriculture in Kenya, and the notable production challenges due to economic water scarcity and food insecurity, strategic conceptual and empirical analysis in the context of the crisis, which would guide policy-makers and development practitioners in their efforts to ensure increased food production through efficient water management, is sparse. This paper provides an avenue for a practical response to Article 7 of the Paris Agreement (UNFCCC

2016) to enhance adaptive capacity, strengthen resilience and reduce vulnerability of smallholder farmers to climate change, hence contributing to sustainable development of the country.

### *1.2 Objectives of the Study*

The study investigated the best practices in rainwater harvesting systems in Kenya, working principles and experiences facing smallholder agriculture in light of climate change and food insecurity. Specifically, the following objectives were addressed: (i) to assess the rainwater harvesting technologies in use in the country; (ii) to characterize their application; and (iii) to guide policy-makers and practitioners in selecting appropriate technique suitable for local needs and contexts.

### *1.3 The Principle of Rainwater Harvesting*

Rainwater harvesting is mainly practised in arid and semi-arid areas where surface run-off is intermittent, is based on the utilization of run-off, and requires a run-off producing area (catchment) and a run-off receiving area (cropped area and/or storage structures). Therefore, each RWHI management system, except in situ water conservation technology (see Fig. 1), should have the following components: run-off producing catchment, run-off collection (diversion and control) structures and run-off storage facility (soil profile in cropland or distinct structure, farm ponds, tanks, water pans, earth dams, sand dams, subsurface dams, etc.) (Mekdaschi and Liniger 2013).

## 2 Methodology

### *2.1 Study Area*

This study was carried out between August 2014 and February 2015 and focused on arid and semi-arid areas (ASAL) in Kenya. ASAL areas cover more than 80% of the country and experiences water resource scarcity. Rainfall is highly erratic both in total amount and in its distribution overtime, which result in high risk of drought and intra- and off-seasonal dry spells. Arid and semi-arid regions in Kenya receive an average annual rainfall of 300–600 mm (Republic of Kenya 2015). Studies show that the agro-humid periods (i.e. the growing periods for annual crops) have reduced considerably in these regions (Malesu et al. 2012). Persistent water scarcity and low crop yields are further explained by high levels of potential

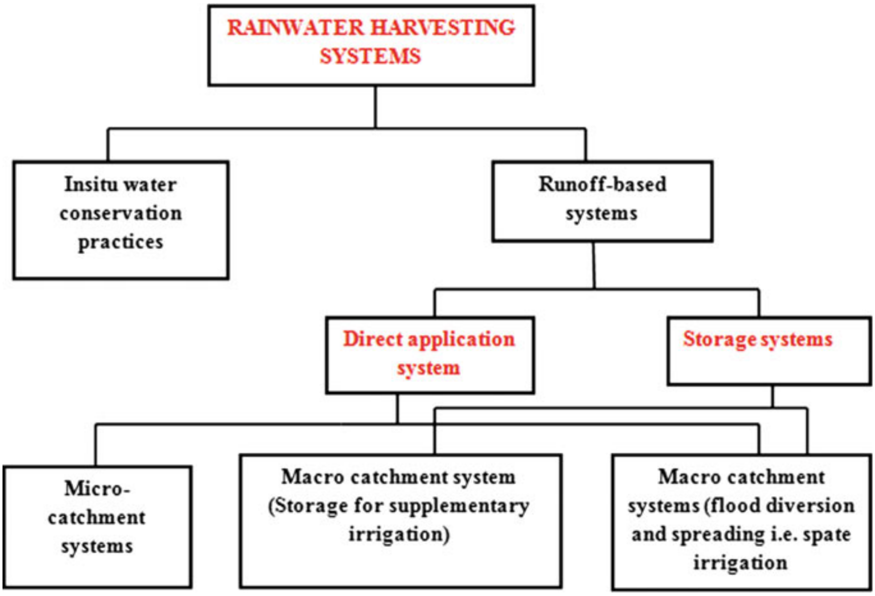


**Fig. 1** Adopted classification of RWH systems. *Source* Adapted from Ngigi (2006)

evapotranspiration and poor rainfall partitioning leading to large proportion of water flows which is not available for crop production. This has often led to severe crop and livestock losses leading to perennial food shortages and over-reliance on emergency food-based interventions to meet local food deficit. Rapidly decreasing rainfall during the agro-humid periods has pushed several households to adopt various agricultural water management practices, such as bunds, ditches and farm ponds.

## *2.2 Methods*

To obtain primary data, we undertook interviews with key informants using a schedule, made field observation and two stakeholder workshops. Key informants were purposefully identified from relevant government and non-state institutions, and practitioners in RWHI. The primary information gathered was on best practices in RWH in the country. In addition, the study benefited from on-the-ground data and experiences during study visits in different areas where the technologies are being practised. Relevant literature from refereed journals and reports from government ministries and development agencies were reviewed to assess location and context-specific RWH technologies and quantify their benefits. These constituted the secondary sources of information.

# 3 Results

## *3.1 Rainwater Harvesting Systems in Kenya*

Rainwater harvesting systems in Kenya can be classified into three main categories: micro-catchment systems, macro-catchment systems and in situ systems (Ngigi 2006; Biazin et al. 2012) (Fig. 1).

### 3.1.1 Micro-catchment RWH Systems

Micro-catchment RWH systems collect surface run-off from small catchments and store rainwater in the soil profile for dry-spell mitigation. The most commonly applied micro-catchment rainwater harvesting techniques in Kenya include pitting, contouring, terracing and micro-basins (Table 1).

**Table 1** Micro-catchment rainwater harvesting—overview of the most commonly practised systems in sub-Saharan Africa

| Types of micro-catchment systems | Description |
|---|---|
| Pitting (Zai pits and trenches) | • Zai pits: a grid of planting pits is dug across plots that could be less permeable or rock-hard; organic matter is sometimes added to the bottom of the pits<br>• Trenches: pits are made along the contour sometimes with a bund downslope either staggered or continuous to check the velocity of run-off, conserve moisture and increase groundwater recharge |
| Contouring (stone/soil bunds, hedgerows and vegetation barriers) | • Stone and soil bunds: a stone or sometimes earthen bank of 0.50–0.75 cm height is piled on a foundation along the contour in a cultivated hill slope, sometimes stabilized with grasses or other fodder plant species<br>• Hedgerows: within individual cropland plots, strips of land are marked out on the contour and left uncultivated in order to form permanent, cross-slope barriers of naturally established grasses and herbs. Alternatively, shrubs are planted along the contour |
| Terracing (Fanya Juu and hillside terraces) | Bunds in association with a ditch, along the contour or on a gentle lateral gradient, are constructed in different forms. The Fanya Juu terraces are different from many other terrace types in that the embankment is put in the upslope position |
| Micro-basins (e.g. Negarims, half-moons) | Different shapes of small basins, surrounded by low earth bunds, are formed to enable the run-off to infiltrate at the lowest point, where the plants are grown. The differences between structures are in their shapes, Negarims (diamond) and half-moons (semicircular) |

*Source* Malesu et al. (2012), Biazin et al. (2012)

### 3.1.2 Macro-catchment RWH Systems

This is the collection of surface run-off from macro-catchment systems with water storage for supplemental irrigation. Macro-catchment systems collect run-off from external catchments and divert it into storage structures. The catchment area for macro-catchment rainwater harvesting techniques ranges from less than 2 ha to over 50 $km^2$. These techniques are becoming increasingly popular in semi-arid counties of Kenya (e.g. Machakos, Laikipia and Kitui). The most commonly applied macro-catchment rainwater harvesting techniques include cisterns, earth dams, water pans and groundwater dams (sand dams and subsurface dams) (Table 2).

### 3.1.3 In Situ RWH Systems

In situ RWH systems maximize infiltration, reduce surface run-off and soil evaporation and improve soil moisture conservation. These techniques do not need a run-off-inducing catchment area; rather, they are aimed at enhancing rainfall infiltration and reducing soil evaporation. The most commonly applied in situ

**Table 2** Macro-catchment rainwater harvesting—overview of the most commonly practised systems in sub-Saharan Africa

| Types of macro-catchment systems | Description |
|---|---|
| Cisterns | Run-off 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. In most cases, settling basins are attached in front of the inlet to reduce sedimentation |
| Farm ponds | An excavated subsurface run-off storage structure, mainly for small-scale irrigation. Farm ponds come in many shapes and sizes—irregular, circular or rectangular with vertical or slanted walls. The sizes range from 10 to 1000 $m^3$ |
| Earth dams and water pans(micro dams) | Larger-sized rainwater storage systems. They are often constructed around foots of hill slopes to store the run-off from ephemeral or perennial rivers. The reservoirs are neither plastered at their walls nor covered on their surfaces |
| Groundwater dams (sand dams and subsurface dams) | Dams 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. Hence, the sand will reduce evaporation and contamination of the water in the sand body behind the dam |

*Source* Ngigi (2006), Biazin et al. (2012)

rainwater harvesting and management practices in Kenya include ridging, mulching and various types of furrowing and conservation tillage (Table 3).

## 3.2 Rainwater Harvesting Irrigation Technologies in Kenya

Rainwater harvesting irrigation technologies in Kenya include on-farm pond systems, roof water catchment systems, ground dam systems (sand and subsurface dams), rock outcrop catchment systems and micro-catchment in situ rainwater conservation systems.

### 3.2.1 On-farm Pond Systems

Farm ponds are excavated subsurface run-off storage structure, mainly for micro- or small-scale irrigation. In Kenya, farm ponds come in many shapes and sizes—irregular, circular or rectangular with vertical or slanted walls. The sizes range from 10 to 1000 $m^3$ depending on farmer's financial capability and intended water uses (Ngigi et al. 2014). While farm pond can greatly unlock the potential of rainfed agriculture, their success is limited by high water losses through evaporation and seepage, siltation, safety and health risks.

Farm pond technology has been widely adopted by smallholder farmers in Kitui, Laikipia and Nakuru counties in Kenya due to its simplicity, cost-effectiveness and economic impacts (Ngigi et al. 2014; Malesu et al. 2006). However, the pressing challenge arises around the tearing of pond lining, especially by animals. During dry season, the lining material often contracts and rips (Malesu et al. 2012) if adequate shrinkage allowance is not considered. Other challenges include water losses, in addition to environmental, health and safety risks. However, these challenges could be adequately addressed if the pond is lined with a thick

**Table 3** In situ rainwater harvesting—overview of the most commonly practised systems in sub-Saharan Africa

| Types of structures | Description |
|---|---|
| Ridging | Basins that are wider than the traditional furrows are created either by manual hoeing or during tillage using a modified ploughing instrument. They can be designed to be tied every 3–6 m distance for holding water and facilitating infiltration in low and erratic rainfall areas |
| Mulching | The use of both crop residues and material from non-cultivated areas, including stones, aimed at covering the soil. This improves infiltration of water into the soil and prevents evaporation out of the soil |
| Conservation tillage | It encompasses a wide range of tillage techniques ranging from non-inversion ploughing and reduced tillage to ripping and subsoiling |

*Source* Malesu et al. (2012), Biazin et al. (2012)

ultraviolet-resistant plastic sheet (to control seepage losses) and roofed either with iron sheet or with shade net (to reduce evaporation, contamination and risk of drowning).

### 3.2.2 Earth Dams and Water Pans

Paradoxically, dryland communities in Kenya experience water scarcity both in rainy season during floods and in dry spells. During rainy season, a lot of run-off is generated that can be stored in surface reservoirs for productive uses. Rainwater harvesting technologies with storage components are a strategy that can mitigate the effects of dry spell on crop production (Fox et al. 2005; Mati 2006, 2007) while also mitigating flooding incidences.

Excavating a depression for water storage and depositing the excavated soil on the lower side as an embankment or dam wall is the typical approach to constructing earth dams. The dam wall is often 2–5 m high and has a clay core and spillway to discharge excess run-off (Petersen 2013). Earth dams and water pans have tremendous potential in drylands of Kenya. The ideal sites for earth dams are natural depressions on steep-sided valleys. However, other available depressions include murram pits often situated along the roads. The ideal soil for constructing a water reservoir should have a high content of clay. However, soil types other than clay can also be used, especially when it is compacted.

In Kenya, earth dams are mainly situated on a public land to allow open and unhindered access to people and livestock (Petersen 2013; Ngigi et al. 2014). In addition, catchment protection is required to minimize erosion and siltation of reservoirs. The protection usually consists of trenches, terraces and planting of grasses or trees in rows along the contours. It also includes building of check dams and silt traps in gullies (Petersen 2006a). Although community-managed earth dams are often affected by poor management, few reservoirs are well managed by local committees that setup rules to ensure water is used for intended purposes and any form of pollution is controlled (Malesu et al. 2012; Petersen 2013; Ngigi et al. 2014). In such cases, animals are kept away from drinking water directly from the dam to help maintain the structures and prevent pollution.

Although earth dams are appropriate in drylands of Kenya, they suffer from a number of constraints common to such environment (Petersen 2006a). First, high temperatures and prolonged droughts will result in evaporation losses from open reservoirs. Second, their capacity is reduced by siltation, especially during severe storms. Third, water in open reservoirs is prone to contamination, especially from livestock. Finally, there is a high risk of children and livestock drowning in a reservoir. Water reservoirs should be fenced to reduce such risks (Malesu et al. 2012; Ngigi et al. 2014).

### 3.2.3 Groundwater Dams (Sand Dams and Subsurface Dams)

The regions with huge potential for sand and subsurface dams (SSD) are arid and semi-arid areas, which occupy over 80% of the Kenya's land mass (Malesu et al. 2012; De Trincheria and Nissen-Petersen 2015). Such areas are ideal for sand and subsurface dams because of several reasons. First, there are several ephemeral streams with coarse sand and water holes. Second, the topography allows construction of weirs and dam embankments (De Trincheria and Nissen-Petersen 2015). Third, there are minimal evaporation and seepage losses due to underground storage and water-tight floors, respectively. Finally, the cost of construction is often low, and minimal maintenance or repairs are required (Petersen 2006a, 2013). On average, up to 35% of water can be extracted from sand and subsurface dams (Petersen 2006a, 2013).

In semi-arid areas of Kenya, sand dams play a pivotal role in water supply for micro-irrigation, livestock and household uses (De Trincheria and Nissen-Petersen 2015). Groundwater dams are commonly found in semi-arid areas of Kenya, especially in the Kitui, Machakos and Makueni counties.

Sand dams are masonry water barriers constructed across ephemeral sandy river beds. The reinforced dam wall, which is constructed at single or successive stages, traps sand upstream and stores water in the voids between sand particles. In addition, the dam wall intercepts subsurface stream-flow to increase water storage. Once the dam is full of sand, there is no further sand deposition or removal by run-off during rains. Rather, the extra incoming sand is washed away downstream and could be used to develop other sand dams in cascades whenever feasible. Sand dams are widely used in semi-arid areas where annual stream-flows vary from high flows following rains to negligible or no flows during the dry season. This type of rainwater harvesting yields enough water to support livestock, household use, or small-scale irrigation through hand watering, treadle or hand pumps, and low-head drip irrigation (Malesu et al. 2012; Ngigi et al. 2014).

Unlike sand dams that occur along streams with width ranging from 5 to 20 m, subsurface dams are built across a sandy dry river bed to a height of 0.6 m below the surface of the sand. In addition, subsurface dams tend to occur along the stream with width ranging from 20 to 100 m. Contrary to sand dams, which are vulnerable and often damaged by storms because their walls protrude above the surface of the river bed; floodwater passes safely over subsurface dams. Whereas sand dams experience evaporation losses until the level of water in the sand drops to 0.6 m below the sand surface, subsurface dams do not suffer such losses because the maximum water level is below the sand surface where capillary action cannot draw water upwards.

While sand and subsurface dams have limited water storage capacity, they are ecologically sustainable due to minimal negative environmental and social impacts. Besides reducing the risk of water pollution by preventing direct contact with pollutants, sand and subsurface dams are constructed on public natural watercourses and therefore less likely to provoke conflicts with regard to ownership. Moreover, they are socially acceptable because they improve the traditional source of water

(Petersen 2013). This has raised a sense of communal ownership for such structures, and desire to maintain and use them sustainably. Finally, there is no danger of disasters because the surface area can be used in the same way before and after their construction.

### 3.2.4 Roof Water Catchment Systems

Roof water harvesting is widely practised in Kenya. Currently, the regulations and guidelines enforcing rainwater harvesting for all public institutions are under consideration by the government of Kenya. Roof water harvesting provides clean water for both domestic use and irrigation. The size of the roof catchment determines the amount of water that can be harvested in a given area and thus the tank size. The amount of water harvested is determined by the roof catchment area and the amount of rainfall. Roof water can be stored in underground or above ground tanks.

Roof water run-off has several advantages over ground generated run-off. First, the run-off generated from the roofs is clean. Hence, not much is required to sieve and filter, making the water ideal for irrigation. Second, roofs are at least 2 m above the ground and therefore provide greater choice to harvest and store run-off either above or below ground. When full, water stored above the ground tanks can generate enough force to operate irrigation systems. Third, maintenance of roof catchment systems requires little time and energy as compared to other systems. For the roof catchment systems, all that is required is monitoring to remove debris and organic depositions along the gutters, downpipes and screen box. Finally, roof water is free from chemical pollutants found in surface run-off and groundwater, making it suitable for consumption and irrigation. However, amount of water generated from the roofs is comparatively small. The average volume of water harvested from roofs is in the range of 30–60 $m^3$. This means that the area to be irrigated is also small. The roof catchment system can be expensive depending on the systems size and rainwater harvesting technology use. A roof water harvesting system may cost between US$200 and US$2000 depending on the size.

### 3.2.5 Rock Outcrop Catchment Systems

The rock outcrop catchment systems catch and concentrate surface run-off into a storage structure for productive use (IRHA 2011). Rock outcrops can collect up to 90% of total rainfall amounts. Most drylands in Kenya particularly in lower eastern region have suitable sites with exposed rock outcrops for rock catchment systems (Petersen 2006c). Through development of rock surface into a catchment, the run-off can be harvested and stored for domestic and livestock use to mitigate dry season water shortages. The potential for scaling-up rock catchment system in Kenya is enormous. For example, Kitui County has more than 400 developed rock catchment systems that supply water for many households and schools. Rock catchment can support kitchen gardening and small-scale horticultural production under drip irrigation and greenhouses which allows high efficiency of water use. Like roof water catchment systems, rock water harvesting provides fairly clean water for both irrigation and domestic use. The size of the rock catchment is, however, much bigger owing extensive rock outcrops depicting large surface areas.

### 3.2.6 Flood Diversion and Spreading (Spate Irrigation) Systems

Run-off diversion and spreading (or spate irrigation) collects, diverts and stores ephemeral channel flow for irrigation of crops, fodder and trees and for ground-water recharge (Malesu et al. 2012). This system allows optimal use of flood water, especially in semi-arid and sub-humid agro-ecosystems. Surface run-off can be collected from a wide range of catchments, such as roads, home compounds, hillsides and open pasture lands and may also include off-stream system where the channel water either floods over the river banks onto adjacent plains or is forced to leave its natural course and conveyed to nearby fields (Malesu et al. 2012).

Flood diversion has a huge potential to enhance productivity of arable and grazing lands (Petersen 2006b). Floodwaters often have high levels of sedimentation that provide source of soil fertility to inundated farms (Malesu et al. 2012). This type of irrigation is relatively cheap to implement and can be a viable alternative where irrigation water from other sources is not readily available or too costly. Unlike surface or subsurface dams, run-off irrigation does not require water pumping and therefore saves energy and maintenance costs (Petersen 2013). Studies indicate that the amount of annual run-off generated in dryland areas is enormous and could support rainfed agriculture (Malesu et al. 2006). Spate irrigation systems are found in many parts of Kenya, especially in Kitui, Machakos and Laikipia counties. They use minimum diversion and water control structures, and hence cost-effective.

### 3.2.7 Small External Catchment Systems

These include small-scale flood/run-off diversion and spreading either directly into cropland or pasture through a series of contour bunds or into terrace channels and other forms of water retention structures. The run-off is either conveyed through natural waterways, road drainage or diversion/cut-off drains.

Road run-off harvesting is practised in parts of Kenya (e.g., Machakos, Makueni and Laikipia counties), in which flood water from road/footpath drainage is diverted either into storage for supplemental irrigation or into croplands (wild flooding, contour bunds, deep trenches) with check dams. The idea is to improve soil moisture content and hence crop yields. *Fanya juu* terraces, which were previously used with diversion/cut-off drains for soil conservation, especially in Machakos and Kitui counties, have been adopted as in situ RWH system. They are modified by constructing planting pits mainly for bananas and tied ridges (check dams) for controlling the run-off. The outlet is blocked to ensure as much run-off as possible is retained while spillways are provided to discharge excess run-off, which is normally diverted into the lower terraces. Run-off spreading has also been accomplished by contour bunds in Laikipia County. They collect and store run-off from various catchments including footpaths and road drainage. The stored run-off seeps slowly into lower terraces ensuring adequate moisture for crops grown between the terrace channels.

## 4 Discussion

Although rainfed cropping system is the mainstay of African agriculture, over 50% of the rainfall may be lost to non-productive sinks in a season, particularly in the arid and semi-arid areas (Temesgen 2012). Yet, increasing production levels of the smallholder farmers, through better soil and water management techniques, can substantially add to global food production (Temesgen 2012). To significantly increase both green and blue water productivity in arid and semi-arid areas of Kenya, rainwater harvesting techniques should be adopted and upscaled. This will mitigate agricultural water scarcity and allow for increase in crop production levels thus helping to mitigate the food security crisis in the country.

The current share of smallholder contribution to the agricultural sector in Kenya is about 75% while contribution from irrigation is only 5% (Salami et al. 2010). This presents an opportunity to increase agricultural yield in smallholder farms by increasing beneficial water available for transpiration through RWHI. Moreover, smallholder agriculture is projected to be economically sustainable in the future because of expanding urban centres, rapid economic growth and the accompanying demand for more diversified products, mainly fruits and vegetables (Salami et al. 2010).

Small-scale farmers in the vast drylands of Kenya are continually exposed to the risk of climate-induced water resource scarcity that is the major constraint to crop and livestock production. The promotion of rainwater harvesting coupled with water delivery and application systems could improve household income and food security. Various studies suggest that rainwater harvesting in combination with improved soil fertility and good agronomic practices has the potential to unlock rainfed crop production systems particularly in regions subject to dry spells (Gichangi et al. 2007; Mati 2007; Kathuli et al. 2010; Malesu et al. 2012).

Multitudes of rainwater harvesting techniques are in use in Kenya. The techniques and modes of application are context-specific, dependent on diffusion and adoption curve among different communities. The best experiences in an area have the potential to be adapted in another area with similar problems of water scarcity and soil type. Uptake of RWHI mirrors investments on irrigation development by both the government and private sector, that is, slow but progressive. The trend is not in tandem with economic development and food demand, and hence, more investment is required both in research and in infrastructure development.

Rainwater harvesting can provide adequate water supply for multiple uses. It has high potential in saving both human and livestock, especially in the drylands of Kenya. While the investment cost for rainwater harvesting is high, the operation and maintenance cost are low, and hence, it has long-term benefits. However, there is need for continued research to determine the cost–benefit analysis for different rainwater harvesting systems. Depending on the type of the system, yield increase of up to 300% has been reported. Thus, the cost–benefit analysis at different scales should be carried out to determine the impacts in terms of yields for different types of crops, and different farming systems.

Major changes and developments are anticipated in RWHI in Kenya due to increased water and food demand that is aggravated by ensuing climate change and variability. The government and communities are running out of options to curb increasing water shortage and food insecurity, and increased investment is expected if we are to sustain the current economic growth and food demand. Vision 2030 alludes to this fact and proposes increased investment in rainwater harvesting and irrigation development.

Our study has highlighted the significance of the technology in Kenya by bringing forth principles and application based on contemporary research on the best experiences with rainwater harvesting. It is our hope that national and county governments will develop policies for increasing adaptive capacities of smallholder farmers using these technologies.

## 5 Conclusions and Recommendations

Adapting agriculture to temporal and spatial rainfall variability through RWH interventions is a norm rather than exception in dryland environments. Although relatively inexpensive indigenous RWH techniques such as bunds or ditches have been successful in moderating the impact of agriculture water scarcity, the biggest benefits will likely result from investment in modern techniques, institutional strengthening and technological innovations in tandem with climate-smart agriculture.

There is need for policies at both national and county governments on rainwater harvesting technologies to address:

- Persistent food insecurity in the country;
- Article 7 of the Paris Agreement by enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change among smallholder farmers; and
- Sustainable Development Goal 1 and Sustainable Development Goal 2 on addressing poverty and sustainable agricultural production systems.

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# Rainwater Harvesting Options to Support Off-Season Small-Scale Irrigation in Arid and Semi-arid Areas of Zimbabwe

**Menas Wuta, George Nyamadzawo, Blessing Nyamasoka, Rumbidzai Nyawasha, Grace Matayaya, Raymond Nazare, Simon Madyiwa and Jonathan Tsoka**

**Abstract** Rainwater harvesting involves the collection, storage and subsequent use of rainwater for domestic, agricultural and other livelihood activities. It consists of a wide range of technologies used to collect, store and provide water for use by humans and/or human activities such as irrigation and providing drinking water for livestock. In semi-arid areas of Zimbabwe, where rainfall is scarce and insufficient to sustain dryland crop production, rainwater harvesting can form the basis for irrigation in order to improve food security. Some rainwater harvesting and irrigation technologies that are currently in use in Zimbabwe include roof catchment systems, rock catchment systems, ground catchment systems, small dams and sand dams. Roof catchment systems collect water from roof surfaces into storage tanks or the place of use. Rock outcrops provide collecting surfaces for rainwater. Sand dams and small dams or weirs are constructed across streams and rivers to capture and store surface and subsurface flow. These various ways of harvesting rainwater can be linked to different irrigation technologies which include drip, sprinkler and flood irrigation systems. Farmers have adopted different pumping mechanisms to move water from storage to point of irrigation such as use of solar, fuel (petrol/diesel) and manual methods. Although it has been proven that these technologies are beneficial in the dry areas, most of these systems are not well developed and only a few of these technologies are operational. There is therefore need to promote RWHI and include other RWH methods such as roadside divergence ditches which are currently not being used in Zimbabwe.

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## 1 Introduction

In most rural arid and semi-arid areas, including sub-Saharan Africa (SSA), water availability plays a critical role in supporting food security and livelihoods (Baguma et al. 2010). Many sub-Saharan African countries, in general, and Zimbabwe, in particular, lie in water-scarce river basins (Gwenzi et al. 2015). Though freshwater resources are available, they are poorly distributed over the country, resulting in water shortages for agricultural and domestic purposes (Davis and Hirji 2014). Rainwater harvesting (RWH) which involves the collection, storage and subsequent use of rainwater for domestic, agricultural and other livelihood activities (Ngigi et al. 2005; Jebamalar and Ravikumar 2011) can play a vital role in improving water supply. Rainwater harvesting consists of a wide range of technologies used to collect, store and provide water with the particular aim of meeting demand for water by humans and/or human activities (SIWI 2001; Malesu et al. 2008). It also includes the collection and storage of local surface runoff for productive purposes such as irrigation, livestock, agroforestry and domestic use. Rainwater harvesting for domestic and agricultural uses is an old practice that dates back to 4500 BC in the Middle East and India (Sivanappan 1997). Increasing water demand for industrial and domestic uses and the changing climatic patterns, where agricultural seasons are getting shorter and mid-season dry spells are becoming longer and more frequent, have forced most developing countries in arid and semi-arid lands to consider RWH as a supplemental water source (Jebamalar and Ravikumar 2011). RWH may also be considered a key adaptation strategy to the impacts of climate variability and change (Barron 2009).

RWH can be classified into two major categories: ex situ runoff-based systems involving harnessing and storing of water from catchments and in situ water conservation practices which include small basins, pits and bunds/ridges (UNEP 2009). The storage system of the ex situ RWH system is usually used in supplementary irrigation through either direct abstraction of rainwater or diversion of water from storage works and seasonal rivers (UNEP 2009). RWH has advantages in that some of the technologies that can be used are low cost, use relatively cheap and locally available construction materials and have low maintenance costs, and collected rainwater can be consumed without treatment if a clean collecting surface has been used (African Union 2003). In situ RWH technologies collect and conserve rainwater by increasing soil and water contact time, therefore prolonging the time of soil water availability to crops (Munamati and Nyagumbo 2010). The most commonly used in situ RWH technologies in Zimbabwe include tied ridges, infiltration pits, *fanya juus*, dead-level contours, planting basins (*makomba*) and tied contours, while the off-situ technologies include roof catchment systems, rock catchment systems, ground catchment systems, small dams and sand dams.

Rainwater harvesting management for small-scale irrigation (RWHI) involves the concentration and storage of rainwater from a large catchment area so as to use it in a small target area (De Trincheria et al. 2016). This is ideally practised in the semi-arid/arid areas where due to poor rainfall distribution rainfall is intermittent; therefore, RWHI helps to sustain smallholder agricultural activities (De Trincheria et al. 2016). There are several RWHI technologies which are currently being implemented in Zimbabwe; however, the expansion of these technologies has been limited by the unavailability of resources and the high implementation costs such as dam construction (De Hamer et al. 2008). This trend may change in the near future due to increasing awareness of the potential benefits of using RWHI in rural arid and semi-arid regions (Merrey and Sibanda 2006; UNEP 2009). Efforts by the AFRHINET project to improve technology transfer and information dissemination will go a long way in facilitating upscaling of RWHI in the country. Small-scale irrigation is the application of water to crops at a small scale (usually <0.12 ha) (African Union 2003) in order to enable multiple cropping. The crops are usually used for household food requirements, and any excess is sold locally or at the nearest market (Mabeza and Mawere 2012; Wuta et al. 2014). Even though the technical capacity to develop RWHI technologies is available in the country (Nyamangara 2015), there are socio-economic conditions that prevent their full utilization and exploitation such as inadequate funding and costly irrigation equipment (Nhundu and Mushunje 2010). The severe economic crisis in Zimbabwe which has caused the closure of industries has reduced the number of suppliers and increased the cost of some equipment that can be used for RWHI (Nhundu and Mushunje 2010). It is expected that as the economic conditions in the country improve, some of the costs associated with RWHI will decrease and there will be more available resources to invest in RWHI (Wuta et al. 2014). The government plays an important role in the upscaling of RWHI technologies. This is because they have the capacity to fund the development of infrastructure such as dams for small-scale irrigation, availing loans for small-scale irrigation, capacity building and development of irrigation services (Wuta et al. 2014).

This chapter discusses RWHI technologies currently in use in Zimbabwe, highlighting the advantages and challenges of each system. Though these technologies have great potential to improve rural livelihoods and alleviate poverty, there is limited uptake. This chapter outlines the factors affecting success and uptake of these technologies and proposes some ways of enhancing adoption of the technologies.

# 2 Methodology

## *2.1 Study Area*

This study was carried out in Zimbabwe, located in sub-Saharan Africa, lying between latitude 15° 40′ and 22° 20′ south, and longitudes 25° 15′ and 33° 50′ east with a total land area of 390,760 $km^2$. Zimbabwe has a tropical climate that can be described as sub-humid to semi-arid (Department of Meteorological Services 1981), and the country is divided into five agro-ecological regions based mainly on rainfall amounts (Nyagumbo and Rurinda 2012).

## *2.2 Study Approach*

To generate an in-depth insight into RWHI in smallholder farming areas of Zimbabwe, several methods of data collection were used. These included the use of questionnaires, key informant interviews, informal interviews and direct observations. One hundred questionnaires were administered, and 30 key informant interviews were conducted. A structured questionnaire survey was used to collect data from October 2014 to December 2014 in Chiota, Mutoko and Zvishavane. The data on households were obtained from the district administrators' offices and from the Agricultural Technical and Extension Services (AGRITEX) field extension officers. To manage expectation, farmers were not asked to give figures of income earned, because of the fear that they would under report their incomes, as some would expect financial benefits from the study (Mabeza and Mawere 2012). In addition, key informant interviews were also carried out with non-governmental organizations (NGOs) that are involved in promoting irrigation in small-scale areas (NGOs), equipment traders, research institutions and government departments.

The study also utilized available literature. The materials examined during this review included both published (including World Wide Web articles, journal articles and books, paper maps, aerial photography), and unpublished material, MSc and PhD theses, national inventories, and non-governmental material, draft reports, newsletter articles, conference proceedings and consultancy reports. Data gathered were used to identify the RWHI technologies in use and, from the stakeholders' perspective, understand the advantages and constraints associated with the use of each system.

# 3 Current RWHI Practices and Technologies in Zimbabwe

## *3.1 In-Field RWHI Systems*

Traditionally, runoff water harvesting technologies have been widely promoted across the country and especially in the dry areas as a way to enhance water productivity (Gumbo et al. 2012). Government- and donor-funded schemes have prioritized research and dissemination of these in situ technologies, resulting in their widespread use across arid and semi-arid regions of Zimbabwe (Motsi et al. 2004; Mutekwa and Kusangaya 2006; Gumbo et al. 2012). Examples include tied ridges, planting basins and infiltration pits, which are dug along contours to harvest rainwater (Table 1) (Motsi et al. 2004).

### 3.1.1 Infiltration Pits

Infiltration pits are deep trenches dug along the contour channel to trap runoff and increase infiltration (Mutekwa and Kusangaya 2006). This technique originated in Zimbabwe from a farmer in Zvishavane (Phiri and Bussink 1995). They are also known locally as '*chibatamvura*', and they are an example of a farmer-driven innovative soil and water harvesting practice. The pits are dug along the contour, and size varies and can be 2 m long, 1 m wide and 1 m deep (Mutekwa and Kusangaya 2006). The water collected in the pits helps to build-up groundwater

**Table 1** In-field rainwater harvesting technologies currently in use in Zimbabwe

| Researchers/Organization | Technology in use | Area |
|---|---|---|
| Motsi et al. (2004) | Tied ridges, infiltration pits and *fanyajuus* | Mudzi, Gutu and Chivi |
| Mugabe (2004) | Infiltration pits | Chiredzi |
| Mutekwa et al. (2005) | Tied ridges, infiltration pits and *fanyajuus* | Chivi, Masvingo |
| Mupangwa et al. (2006) | Tied ridges, infiltration pits and *fanyajuus* | Gwanda |
| Mutekwa and Kusangaya (2006) | Tied ridges, infiltration pits and *fanyajuus* | Ngundu, Masvingo |
| Nyagumbo et al. (2009) | Dead-level contours | Gwanda |
| Mazvimavi et al. (2010) | Planting basin (*Makomba*) | Chipinge |
| Munamati and Nyagumbo (2010) | Dead-level contours | Gwanda |
| Mupangwa et al. (2012) | Dead-level contours & infiltration pits | Gwanda |
| Gumbo et al. (2012) | Dead-level contours | Mazvihwa and Gwanda |

reserves which provide deep rooting crops such as trees with water (Berger and Gold 2004). A survey conducted in ward 25 (Ngundu) of Chivi district in Masvingo showed that infiltration pits were adopted by 61% of the population of 9031 (Mutekwa et al. 2005).

### 3.1.2 Fanya Juu

*Fanya juu* originated in Kenya and involves throwing of soil excavated from the drainage channel to the upper side of the channel (Motsi et al. 2004). The channel depth is usually 50–60 cm with cross-ties at 10-m intervals. Farmers in many semi-arid regions have successfully used this water harvesting technology to increase crop yields relative to conventional tillage (Hagmann and Murwira 1996; Motsi et al. 2004). Uptake of this technology is very limited because of the demand for labour to dig channels and construct ridges.

### 3.1.3 Tied Contours

Contours ridges (Fig. 1) are found in most fields throughout the semi-arid regions of Zimbabwe, and they dispose of precious water from the fields (Nyamadzawo et al. 2012). Most fields in rural areas in Zimbabwe have contours because it was a requirement by the colonial government (Gumbo et al. 2012). Farmers were forced to construct contour ridges, and failure to comply was a serious offence (Gumbo et al. 2012). Tied ridges are made up of ridges that are 15–20 cm high made of earth with an upslope furrow which accommodates runoff from a catchment strip between the ridges. Ridges may be 1.5–10 m apart. Small earthen ties can be made within the furrows to prevent lateral flow of water (Critchley et al. 1992). The objective is to collect runoff and store it in the soil profile close to plant roots (UNEP no year). The modified tied contours systems will retain water in-field which will enable crops to grow better during dry spells and drought periods compared to standard contours (Motsi et al. 2004). To date, there are a few studies that have evaluated the potential benefits of using the tied contour ridges for water harvesting in semi-arid smallholder farming areas of Zimbabwe (Nyagumbo et al. 2009; Nyamadzawo et al. 2012)). However, it has been shown that maize yields increased from $<0.6$ t $ha^{-1}$ under standard contours to between 1.5 and 2 t $ha^{-1}$ under tied contours (Motsi et al. 2004).

### 3.1.4 Dead-Level Contours

A dead-level contour (Fig. 2) is a modification of the standard graded contour and has a zero-grade channel upslope of an earth ridge (Gumbo et al. 2012). It is constructed to collect runoff from within and outside the field and store it in a

**Fig. 1** Photograph showing tied contours, Marange, Zimbabwe. *Photograph* George Nyamadzawo

channel instead of diverting it away from the field as is done by standard graded contours (Gumbo et al. 2012). The water will then slowly percolate into the soil on either side of the contour, providing vital moisture to the adjacent crops during dry spells. The reason for this modification is to improve crop productivity through better moisture retention (Gumbo et al. 2012). The dead-level contour is a farmer-driven innovation developed in 1988, which led to the adjustments and modification of the standard graded contours (Hagmann and Murwira 1996). In 1988, about 10 farmer innovators in Zvishavane and Chivi districts of Zimbabwe were part of the Indigenous Soil and Water Conservation in Africa Project to share their knowledge and discuss dead-level contour innovations (Hagmann and Murwira 1996). After that, the technology of dead-level contours has spread, and the number of adopters increased. The major limitation of this technology is its demand for labour for construction of the contour channels and ridges (Gumbo et al. 2012). The conversion of standard graded contours into dead-level contours has resulted in higher yields. Nyagumbo (2015) reported that maize yield increased by 38% under dead-level contours compared to standard contour ridge system. Average maize yields are 0.6–0.8 t ha for fields with standard graded contours and 1.5–2.5 t ha for fields with dead-level contours, while for sorghum, the average yields are 0.2 and 4.0 t ha, respectively (Nyagumbo 2015).

Farmers in Manama Communal Area in Gwanda district of Zimbabwe have modified the standard contour ridges and added infiltration pits and called this technique Manama In-field Rainwater Harvesting Storage Facility (Mupangwa et al. 2006). This was after the realization that farmers were losing water from the standard contour after harvesting it. The infiltration pits help to reduce the rate of runoff (Mupangwa et al. 2006).

**Fig. 2** Dead-level contour used in Zvishavane, Zimbabwe. *Photograph* Menas Wuta

Dead-level contours entail the construction of zero-gradient channel upslope of the earth ridge which often contain infiltration pits or storage tanks as shown in Fig. 2 (Gumbo et al. 2012). The depths of channels and pits differ in size depending on soil type to account for different rates of infiltration, and often times in light-textured soils, the pits are compacted with heavier soils from elsewhere to minimize deep percolation. In the drier areas (mean annual rainfall $\leq 500$ mm), infiltration pits are temporarily covered to reduce the loss of water through evaporation (Gumbo et al. 2012).

### 3.1.5 Ridging/Tied Ridging

The objective of this in situ water harvesting technology is to catch rainwater under rain-fed systems and increase the soil–water contact time to improve infiltration while at the same time reducing runoff (Motsi et al. 2004). They have the advantage that farmers can use cattle-drawn ploughs to make ridges, reducing the human labour required, and hand hoes are used to tie the ridges (Motsi et al. 2004). Extensive research conducted between 1988 and 1996 under the CONTIL, a collaborative project between Agricultural Technical and Extension Services

(AGRITEX) and German Technical Cooperation (GTZ) evaluated three reduced tillage systems (mulch ripping, clean ripping and tied ridging) against two traditional systems (conventional tillage and hand hoe), and it was observed that maize yields can increase up to 3.6 t/ha (Marongwe et al. 2012).

### 3.1.6 Planting Basins

In Zimbabwe, basin tillage (*makomba*), which is a modification of the *zai* system once used in West Africa, has been widely promoted under Precision Conservation Agriculture (PCA) (Twomlow et al. 2008). The basins (15 cm × 15 cm × 15 cm) (Fig. 3) are used to accommodate seed and mineral/organic fertilizers, and they remain partially covered to collect runoff water (Nyamangara et al. 2013). The basins were initially introduced targeting poor and vulnerable households without access to draft power (Nyamangara et al. 2013). By the 2007/2008 season, more than 50,000 households had tried the PCA technology and it resulted in increased average cereal yields by between 50 and 200% in more than 40,000 households (Twomlow et al. 2008). However, many farmers have abandoned the technology because of the labour required to dig the holes before the onset of rains (Twomlow et al. 2008). There are research efforts to develop animal-drawn and tractor-drawn implements to dig holes so as to lessen the burden on farmers and to increase the adoption of the technology (Nyamugafata 2015).

**Fig. 3** Planting basins dug during dry season to facilitate harvest of initial rainwater in Gokwe, Zimbabwe. *Photograph* Menas Wuta

## *3.2 Ex Situ RWHI Systems*

The ex situ RWHI technologies currently implemented in Zimbabwe can be divided into four systems: roof catchment systems, rock catchment systems, ground catchment systems, and check and sand dams (Wuta et al. 2014). These systems can be used to supply water during periods of scarcity (De Hamer et al. 2008). The type of RWH system to use is dependent on the environment, available resources and the intended purpose of the harvested water (Wuta et al. 2014). Rainwater harvesting interventions to date are primarily used to increase crop, fodder, food and timber production or to provide domestic, public and commercial supplies of water (UNEP 2009; Wuta et al. 2014). In Zimbabwe, there is very limited use of many of the ex situ RWHI technologies as a consequence of socio-economic conditions such as lack of awareness among the relevant stakeholders, inadequate funding, high cost of equipment migration of technical and human resources to other countries (Nhundu and Mushunje 2010). More research and extension efforts are required to create awareness among farmers about the available technologies and also to engage funding organizations to pour resources into research and development (Wuta et al. 2014).

### 3.2.1 Roof Catchments

Capturing rainwater from rooftops is a popular method for collecting water for domestic and small-scale irrigation use (De Trincheria et al. 2016). Roof catchments are affordable and easy to install and can be used on public infrastructure, for example schools and clinics (UNEP 2009; Wuta et al. 2014). Roofs with corrugated iron sheets or tiles are most preferable as they are the easiest to use and provide clean water (UNEP 2009). Thatched or palm leaves surfaces are feasible; however, they tend to be difficult to clean and they taint the runoff (Gaia 2013). The collected water can be stored in plastic, metal or cement tanks (De Trincheria et al. 2016). This ex situ method is the most commonly promoted in rural Zimbabwe (Wuta et al. 2014). It is easy and cheap to establish because in a number of cases all that is required is a container to collect water from the roof. Some rural schools and clinic are now using this technology (Wuta et al. 2014).

### 3.2.2 Rock Catchments

Rock outcrops can also be used as collecting surfaces for RWHI, and the structures built to collect water are called rock catchments (Nissen–Petersen 2006). Reservoirs for storing runoff from rock catchments may be a tank built near the rock catchment or a rock catchment dam built on rock surface or near the rock surface (De Trincheria et al. 2016). Runoff water gravitates into the reservoir naturally or is diverted by garlands which are built by rock/brick and mortar (Wuta et al. 2014).

**Fig. 4** Roadside diversion ditches can be used to collect runoff water which can collect in roadside ponds. *Photograph* Means Wuta

For rock catchments, a significant proportion of water can be obtained from almost flat rock where collecting channels drain into pipes that lead to tanks (Wuta et al. 2014). If access to the catchment area by wildlife, livestock and humans can be prevented, a protected rock catchment may collect water of high quality, as long as the surface is cleaned before runoff is collected (Wuta et al. 2014).

Rock catchment systems can also be likened to a roadside diversion ditch which collects runoff from the road (Fig. 4) and is common in countries like Kenya (Ngigi 2003). Cut-off drains deliver rainwater runoff from roads onto cultivated land. This runoff water can be collected in roadside ponds, water into ground tanks, small earth dams or land for seasonal irrigation (Infonet 2015). Though this technology has potential, in Zimbabwe harvesting of water from roadsides is not a common practice (Wuta et al. 2014).

### 3.2.3 Small-Scale Surface Dams

Small dams or weirs are constructed across streams and rivers to capture surface flow (Wuta et al. 2014). Surface dams are artificial, usually formed by constructing a dam across a river or by diverting a part of the river flow and storing the water in a reservoir (FAO 2010). Small-scale surface dams can be constructed using earth or masonry. Earth dams are among the easiest ways to store rainwater available (FAO 2010). In most small-scale farming areas of Zimbabwe, most of the small surface dams/wells are constructed within the individual farmer gardens for the provision of water for irrigation of crops and for other domestic purposes (Wuta et al. 2014). The gardens are usually located in seasonal wetlands. Dams built across streams and rivers tend to be expensive for smallholder farmers and therefore require external financial support (Nyamadzawo 2014). Figure 5 shows a weir constructed across a river in Matobo district in Zimbabwe.

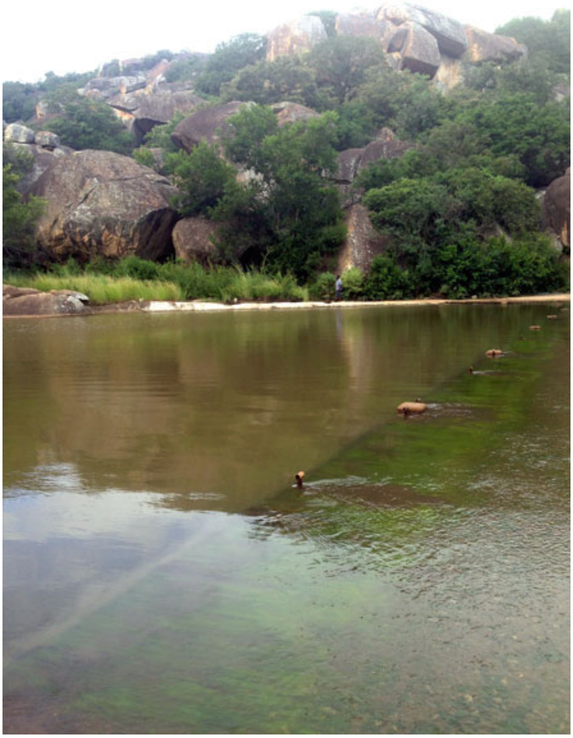

**Fig. 5** Weir constructed across a river in Matobo district, Zimbabwe. *Photograph* Rumbidzai Nyawasha

Surface dams can be built with locally available material and labour. However, building the dam still requires relatively high investments depending on the size and is labour-intensive, and specific expertise is needed (Wuta et al. 2014). Before starting a groundwater project in an area, the community must be intensively involved to create a sense of ownership, which has proven to be the key factor in successful construction and maintenance of groundwater dams (Nhundu and Mushunje 2010). Communities can cover about 40% of the overall construction costs by being involved in the construction of the storage dams and through provision of labour and locally available raw materials and management groups (FAO 2000; Wuta et al. 2014). The other costs can be covered by NGOs or government departments.

### 3.2.4 Ground Catchment Systems

Ground catchment systems refer to the different groundwater recharge techniques that release water from above the ground into the groundwater aquifer via soil percolation (Wuta et al. 2014; Nilsson 1988). With direct groundwater recharge, water moves from above-ground into the aquifer via soil percolation (Bhattacharya 2010). This method can make use of techniques such as infiltration basins to enhance the natural percolation of water into the ground (Wuta et al. 2014). The other method that can be used is the spreading basin method, where spreading of water in surface basins excavated in the existing terrain takes place. This method tolerates more turbid water than other recharge methods (O'Hare et al. 1986; Bhattacharya 2010). Recharge shafts, pits and basins can also be used, and they all vary in shapes and sizes.

Currently, there are very few groundwater dams that have been constructed in Zimbabwe (Wuta et al. 2014). However, there is a huge potential for groundwater dams due to the presence of many ephemeral sand rivers across the country (Rockstrom 2000). Although the technical capacity and skill to carry out the construction is available locally, lack of financial resources and funding from the central government has resulted in a few of these dams being constructed (Wuta et al. 2014). The lack of information dissemination on groundwater dams, especially in rural areas and among extension officers, has also resulted in a knowledge gap resulting in underutilization of groundwater dams (Nhundu and Mushunje 2010). Smallholder farmers can construct small underground dams near their homesteads to capture runoff, but currently very few farmers have taken up this technology (Wuta et al. 2014). Training workshops as well as demonstration trials that showcase how the technologies work are effective ways to create awareness and uptake (Wuta et al. 2014).

### Sand Dams

A sand dam is a reinforced concrete wall built across a seasonal river bed, 2–4 m high and up to 90 m across (Maddrell and Bown n.d.). A pipe can optionally be built into the dam, going up to 20-m upstream (Maddrell and Bown n.d.). During the rainy seasons, water floods and flows over the dam and in the process, sand particles settle in the reservoir, while the lighter silt is washed downstream (Hussey 2003). The sand that accumulates upstream of the dam provides groundwater storage capacity (Fig. 6). The topographical conditions govern to a large extent the technical possibility of constructing the dams as well as achieving sufficiently large storage with suitable recharge conditions and low seepage losses (De Hamer et al. 2008). This system is suitable for rural areas with semi-arid climate in order to store only seasonally available water to be used during dry periods for livestock, small-scale irrigation and domestic use (Hussey 2003). In semi-arid areas of Zimbabwe, most rivers are seasonal and these aquifers can be used to provide water for domestic use, livestock watering and dip tanks, commercial irrigation and market gardening. In this situation, the use of alluvial aquifers of non-perennial rivers can provide an important additional water resource (Moyce et al. 2006). A study in Umzingwane estimated that 62% of stored water can be abstracted, while only 38% is lost due to evapotranspiration (De Hamer et al. 2008). Evapotranspiration losses were low because at depths >0.9 m evaporation becomes

**Fig. 6** A sand dam built across a river in Umzingwane, Zimbabwe. *Photograph* Menas Wuta

negligible (Borst and De Haas 2006). In Zimbabwe, sand dams are mainly found in the southern part of the country, though abstraction and use of water from the river bed is a widespread activity (Hussey 2003).

## 4 RWHI Technologies and Their Link to Small-Scale Irrigation Development

The water harvesting technologies highlighted can be linked to small-scale irrigation systems which vary in size across Zimbabwe. Irrigation systems used by smallholder farmers are determined by several factors which include water source, topography, soils, climate, type of crops to be grown, availability and cost of capital and labour (Mupaso et al. 2014). In addition, the type of irrigation technology available, system design and its associated energy requirements, water-use efficiencies as well as socio-economic, health and environmental aspects will also affect the type of irrigation system (FAO 1997; Wuta et al. 2014). In most small-scale farming areas, the source of water includes shallow wells, small dams, storage tanks and boreholes (Nyamadzawo 2014), making rainwater harvesting an important activity. RWHI can improve agricultural production, food security and the livelihoods of people in the small-scale farming sector (Shimada 1994; Orr and Ritchie 2004; Wuta et al. 2014). Even in wetter regions of Zimbabwe, mid-season dry spells are now common making supplementary irrigation necessary (Nyamadzawo 2014). In the smallholder farming areas, irrigation is also used to extend the growing season of certain crops or to ensure the early planting of such crops as tobacco (Nhundu and Mushunje 2010). Therefore, incorporating RWHI technologies with small-scale irrigation has enabled farmers to do multiple cropping in a single year and instead of only depending on rain-fed staple crop production (Nyamadzawo 2014). Farmers are also now able to grow a variety of crops including horticultural produce for both home consumption and income generation (Shimada 1994; Wuta et al. 2014). RWHI is also important and benefits the most vulnerable members of communities like the elderly or women-headed households in the small-scale farming areas (Nyamadzawo 2014).

## *4.1 Ex Situ RWHI Systems and Small-Scale Irrigation*

Approximately 13,000 ha of irrigated land in Zimbabwe is found in the small-scale irrigation sector (FAO 2000). Currently, 6000 ha is in use, while the remainder 7000 ha requires rehabilitation (FAO 2000; Wuta et al. 2014) although very few of the small-scale irrigation schemes are operating efficiently. Small-scale private irrigation schemes are individually run schemes of less than 2 ha, and in many instances, the individual farmer is responsible for water supply to the farm and all farm operations (FAO 2000; Wuta et al. 2014). These farmer investors are driven by a strong profit motive and are predominantly located in periurban areas or in close proximity to urban areas (FAO 2000). There are some communities of small-scale farmers who share a pump station and delivery line; however, the scheme area is usually below 50 ha with each farmer's landholding averaging 0.5 ha (FAO 2000).

### 4.1.1 Rock and Roof Water Harvesting Structures and Small-Scale Irrigation

Many farmers who practise this type of water harvesting store the water in large containers made either of plastic, metal or brick (Fig. 7). The capacities of such tanks usually range from 1 to 30 $m^3$ of water, and in a lot of instances, the water is used to water small horticultural gardens or for household purposes (De Trincheria et al. 2016).

The water supply can be gravity fed or pumped to facilitate irrigation (Nyamadzawo 2014). In some areas of Zimbabwe, smallholder farmers use fuel-powered (diesel/petrol) or solar-powered pumps for irrigation (Fig. 8) (Wuta et al. 2014).

**Fig. 7** Rock catchment and brick water storage tank in Mutoko, Zimbabwe. *Photograph* Menas Wuta

**Fig. 8** Solar power unit used to pump water for irrigation. *Photograph* Menas Wuta

### 4.1.2 Small-Scale Surface Dams and Small-Scale Irrigation

Irrigation of larger areas often requires more water and bigger investments in irrigation equipment. They also require larger pumps, depending on the sprinkler head, distance and slope the water must traverse, while trickle and drip irrigation (Fig. 9) are the most efficient systems for high-value crop production systems because it is highly efficient (Wuta et al. 2014). In this case, farmers usually organize themselves into groups or schemes and investment in the group schemes is mainly from government and NGOs (FAO 2000; Wuta et al. 2014). These groups tend to be relatively better organized in operation and management of their systems (FAO 2000; Wuta et al. 2014). They are the main contributors to agricultural

**Fig. 9** Drip and sprinkler irrigation investments by farmers. *Photograph* Menas Wuta

production and food security for the country in rural arid and semi-arid areas (FAO 2000; Wuta et al. 2014).

Though irrigation can be beneficial to small-scale farmers, some smallholder schemes have failed and remain underutilized (FAO 2000). Some of the most important factors which affected performance of irrigation schemes in Zimbabwe include improper planning, as some schemes were planned without involving the farmers (Nhundu and Mushunje 2010). Schemes which were planned by consultants without participatory rural appraisal (PRA) experience perform badly as shown by the Ngezi-Mamina, Mambanjeni and Rozva irrigation schemes (FAO 2000). The lack of cooperation among farmers, especially in areas such as marketing, hiring of transport as well as the type of management, affects the performance of the schemes (FAO 2000; Wuta et al. 2014). In addition, for government-run schemes, farmers do not feel a sense of ownership and they are not worried about efficient utilization of resources (FAO 2000). The type of irrigation method used, whether sprinkler or surface, is also important, because it affects the labour inputs and leisure time for the farmers (Wuta et al. 2014). Farmers on surface irrigation schemes often complain of the high labour demands of the irrigation. This leaves very little time for other important activities such as weeding, spraying and organizing marketing of produce compared to sprinkler irrigation (FAO 2000; Wuta et al. 2014).

### 4.1.3 Groundwater Systems and Small-Scale Irrigation

The use of groundwater systems such as sand dams is mostly prevalent in the southern areas of the country in Gwanda, Matobo and Umzingwane smallholder farming areas. The areas usually receive very low intermittent rains, and they supplement with water found in sand dams (Hussey 2003). Digging and fetching of the water has been done by hand until in recent years when several organizations such as Dabane Trust have assisted farmers by installing, cheap, low maintenance pumps which are easy to use to facilitate with the pumping (Fig. 10). This water is used to irrigate their crops and livestock during the dry season.

**Fig. 10** Simple manual pumping to extract water from a sand dam in Umzingwane, Zimbabwe. *Photograph* Rumbidzai Nyawasha

## *4.2 Challenges of RWHI Upscaling in Zimbabwe*

There are several issues that affect the success of RWHI in Zimbabwe, and these involve policy and regulation, socio-economic as well as cultural factors (Wuta et al. 2014). For instance, the development of irrigation schemes is fragmented because management of water resources falls under different ministries and government departments. This has often resulted in inefficiencies and, at times, conflicts between departments which negatively impacts RWHI (FAO 2000; Wuta et al. 2014). There is also no clear policy regulating upscaling of RWHI technologies. There is a need to raise awareness on the issues pertaining to RWHI since not many people understand the principles of RWHI, and some of them have never practised it (Wuta et al. 2014). It is important to raise awareness of RWHI technologies among practitioners, for example academics, scientists and policy makers (Awulachew et al. 2005; UNEP 2009). The lack of adequate institutional support, institutional set-up and unstable accountability issues may result in confusion on mandate and, in some cases, failure of RWHI upscaling (Awulachew et al. 2005; Wuta et al. 2014). Science and technology actors should be involved in RWHI and avail technologies that are affordable to most of the smallholder farmers (Wuta et al. 2014).

There is a need to target technologies according to socio-economic and bio-physical conditions of rural communities in order to encourage uptake (FAO 2000; Wuta et al. 2014). Initial development costs may be high and unaffordable for most smallholder farmers, as there is a need for the construction of small dams and other water storage facilities which are out of reach of most poor smallholder farmers (UNEP 2009). In addition, the lack of a technology matching the available financial resources, high initial cost of implementing the technology, lack or inadequate access to financial resources, inappropriate land tenure, unfavourable local geology and insufficient capacity among the local communities may also reduce the uptake of RWHI technologies (UNFCCC 2013). Participatory approach in development of RWHI technologies should be implemented to ensure sustainability of programs. It is also important to take into account different cultural and traditional perceptions. For instance, Kallren (1993) reports on failure or rejection of technologies such as RWHI as flowing water is sometimes considered more pure than stored water or rainwater because of self-purification and reservations of the taste of rainwater due to low mineral content.

## 5 Conclusions and Recommendations

There are many technological options for rainwater harvesting and irrigation available for use by smallholder farmers in Zimbabwe. Traditionally, smallholder farmers across Zimbabwe have practised in situ runoff water harvesting technologies such as tied contours, dead-level contours and *fanya juus*. Although these technologies have been more beneficial, especially within the cropping season, it is the ex situ technologies that have the potential for water storage to facilitate supplemental irrigation during the dry season. Ex situ technologies include roof and rock water harvesting, harvesting of off-road runoff, small surface dams and sand dams, and the harvested water can be stored for later use. These various ways of harvesting rainwater can be linked to different irrigation technologies which include drip, sprinkler and flood irrigation systems. Investing in rural water development through RWHI may potentially reduce poverty and improve livelihoods through providing water for agriculture and livestock in arid and semi-arid regions of Zimbabwe. Several factors which include inadequate funding, lack of technical know-how, and lack of appropriate technologies have affected upscaling of these technologies across the country. It is important to conduct capacity building in RWHI in schools, technical colleges and universities to boost institutional capacities. The government should coordinate development and institutional reforms as a way to bring all irrigation functions under a single and stronger government department. One of the greatest impediments to uptake of RWHI technologies is the huge costs associated with it; therefore, there is need to enhance access to institutional support services such as credit facilities and external funding to assist smallholder farmers in establishment. In addition, science and technology actors should play a major role in availing proven RWHI technologies to farmers at affordable prices. Smallholder farmers also need to be linked to markets for sustainable crop production.

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# Improving the Efficiency of Runoff Pond System for Supplementary Irrigation in Arid and Semi-arid Areas of Kenya

**Alex Raymonds Oduor and Maimbo Malesu Mabanga**

**Abstract** With the advent of climate change, semi-arid regions are witnessing increased variability of weather patterns depicted in changes of amount and onset of precipitation, high evapotranspiration demands and increased frequencies of famines. This has exacerbated food security situation, culminating in increased demand for irrigation to mitigate against dry spells and drought. In the semi-arid regions of Eastern Kenya, most farmers are adopting the harnessing of runoff ponds to create water buffer that would be used during the crucial crop-growing stages. Thus, a runoff pond system is comprised of conveyance, storage, abstraction and application mechanisms. However, the efficiency of the system along each component is still low, owing to water losses through poor transmission, seepage, leakage and evaporation. This chapter highlights on experiences of farmers, in Kibwezi East sub-county, Masongaleni location, who had installed 140 ponds by the end of 2013 with new ones still being dug. It goes further to recommend on best practices that could help improve the systems' performance of these runoff ponds, and how lessons learnt from here could help improve similar initiatives in the eastern and southern sub-Saharan Africa.

**Keywords** Runoff water · Leakage · Evaporation · Efficiency
Trapezoidal pond

## 1 Introduction

In the dry Savannas of Africa that include eastern, central and southern regions of the continent, agricultural production is generally characterized by cereal/legume mixed-cropping systems dominated by maize, millet, sorghum and wheat as well as beans, cowpeas and green grams (Ker 1995). More than 95% of the farmed land is

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rainfed (FAOSTAT 2005), with average grain yields of 1.5 t/ha, compared with 3.1 t/ha for irrigated yields (Rosegrant et al. 2002).

An insight into the inventories of natural resources in rainfed regions shows a grim picture of water scarcity, fragile environments, drought and land degradation due to soil erosion by wind and water, low rainwater use efficiency (35–45%), high population pressure, poverty, low investments in water use efficiency (WUE) measures, poor infrastructure and inappropriate policies (Wani et al. 2003a, b; Rockström et al. 2007).

Despite water being the most important driver for four of the Millennium Development Goals, water scarcity is a significant problem for farmers in Africa, Asia and the Near East, where 80–90% of water withdrawals are used for agriculture (FAO/IIASA 2000).

In Kenya, like in many other countries in semi-arid tropics, agriculture is the major contributor and leading sector of the country's economy, accounting for 25% of the GDP, 65% of total exports and more than 18% of formal employment (Van Duivenbooden 2000).

Dryland farming is practised in ecological zones V and VI of Kenya that are classified as arid and semi-arid (ASAL) with average annual rainfall, which is bimodal, ranging from 300 to 900 mm and annual average potential evaporation of between 1650 and 2400 mm (KSS 1980). This denotes a very low rainfall to potential evaporation ratios of 15–40%. The effect of this unpredictable weather is minimal livelihood options. Other than the low soil fertility and poor genotypes, the major constraint to agricultural production is low and unpredictable rainfall. Most dryland regions of the country, therefore, have poverty rates way above the national average (RoK 2002, 2007, 2008). As such, farmers cannot afford farm inputs which are important in increasing crop yields. The situation is exacerbated by economic water scarcity (Mwenzwa 2011).

On the other hand, water quantity per se is not the limiting factor, in many semi-arid tropical (SAT) situations, for increased productivity but its management and efficient use are the main yield determinants. The major water-related challenge for rainfed agriculture in semi-arid and dry sub-humid regions is rather on how to deal with the extreme rainfall variability, characterized by few rainfall events, high-intensity storms and high frequency of dry spells and droughts.

The outrageous nexus between drought, poverty and land degradation has to be broken to meet the Millennium Development Goal of halving the number of food-insecure and poor households by 2015. Substantial gains in land, water and labour productivity as well as better management of natural resources are essential to reverse the downward spiral of poverty and environmental degradation. Runoff ponds, for example, trapezoidal pond presents a potential alternative to the conventional green water supply for agricultural production through supplementary irrigation.

## 2 The Advent of Trapezoidal Runoff Ponds in Kenya

Ponds were introduced in Kenya in the 1920s ostensibly for fish production (Ngugi et al. 2007). A study by Malesu et al. (2006) showed a high density of unlined ponds in Lare sub-county of Nakuru county, Kenya, which were introduced to Lare farmers by Egerton University, the Kenyan Ministry of Water and Rotary Club of Nakuru. These institutions participated in the installation of over 5000 unlined ponds. The ponds are unlined owing to limited seepage rates following the existence of clay soil. The driving factor for the adoption of these ponds is the link with a canning factory located on an average radius of 4 km from Njoro town. Farmers grew green peas on a commercial basis and sold the produce to the canning factory. There was also marked increase in afforestation, with farmers commercializing tree products such as timber on a sustainable basis. To date, the hydrology of the area has significantly improved, thus boosting the ecology of Lake Nakuru.

In contrast to Lare, the lower eastern region of Kenya that encompasses Machakos, Makueni and Kitui counties which fall under the arid and semi-arid agro-ecological zones of Kenya has pervious soils. Thus, water captured in ponds constructed in these regions easily seep and percolate into the underground echelons of aquifers. In response to this challenge, the Swedish-based Regional Land Management Unit (RELMA-in-ICRAF) deployed their top scientists and technologists to pilot lined ponds in Machakos county. The result was the introduction of the truncated pyramidal household runoff ponds lined with jackets of synthetic polymers, i.e. polyvinyl chloride (PVC) material. Because of the successes in these ponds, ICRAF, the World Food Programme (WFP), Government of Kenya, Red Cross and the National Drought Management Authority all formed a consortium for their introduction. Water from the ponds has been used for supplementary irrigation of horticultural crops such as onions, tomatoes, capsicum and green grams. Surprisingly, pond water for poultry production was tried in Kibwezi and fetched very good gross margins. The Kenya Seed Company has records for average farm yields of various crops. Tomato Cal J Variety produces a yield of 12,000 kg/acre while that of Joy F1 variety produces a yield of 32,000 kg/acre.

## 3 Assessment and Improvement of Efficiency for the Runoff Pond Components

### *3.1 Conveyance Mechanisms*

#### 3.1.1 Road Channels and Waterways

Conveyance mechanisms are composed of open structures that include the road channels, the waterways leading to the silt traps, the silt trap division box and the mitre drains. During conveyance, water is lost through evaporation as well as seepage. Since there is adequate amount of runoff generated, the greatest concern for the conveyance system in reference to efficiency of the runoff ponds is on water quality.

In the conventional practice, farmers have control only on waterways, silt traps and mitre drains. This is because farmers have no control over the road reserves as they are public utility unless they border their farms. The roads are often made of the inherent natural soils. If the soil texture has higher percentage of sand, then there is less siltation on the ponds and vice versa.

A lot of silt and organic wastes are washed away along the road channels. This entrainment of silt eventually contributes to the siltation of the reservoir, thus affecting both the reservoir capacity as well as the quality of water therein. The amount of silt entrained along the road channels and eventually to the pond can be determined by using the soil erosion formula presented below. It is, therefore, important to understand the domain of the catchment wherefrom the silt originates.

Soil erosion is given by the Universal Soil Loss Equation as depicted below;

$$A = R * K * L * S * C * P \tag{1}$$

where

- $A$ The average annual soil loss (tonnes per hectare)
- $R$ Measure of the erosive forces of rainfall and runoff
- $K$ Soil erodibility factor
- $L$ Length factor
- $S$ Slope factor
- $C$ Crop management factor
- $P$ Conservation practice factor.

This equation is also adapted to the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Project (WEPP) or the Soil Loss Estimation Model for Southern Africa (SLEMSA) (Elwell 1981; Elwell and Stocking 1982). Knowledge in the amount of silt generated is useful and helps in deciding on silt trapping designs and mechanisms.

Mitigation of the roadside erosion and siltation requires community involvement. The community needs to provide labour and work on the road—which is often about 3–6 m wide—so that it attains a convex shape. On either side of the road, the channels should be at least 1 m wide and 30 cm deep. It should also be stone pitched and/or vegetated to reduce the runoff flow velocity—so as to check on erosion (Fig. 1). Farmers owning land adjacent to the road could divert part of the runoff for borderline tree planting. On sections where channel gradients are steep (>5%), check dams made of twigs are anchored.

The same treatments are applied to the waterways conveying runoff from the road channels to the silt traps. Alternatively, waterways could also be treated with tractor tread stone pitching.

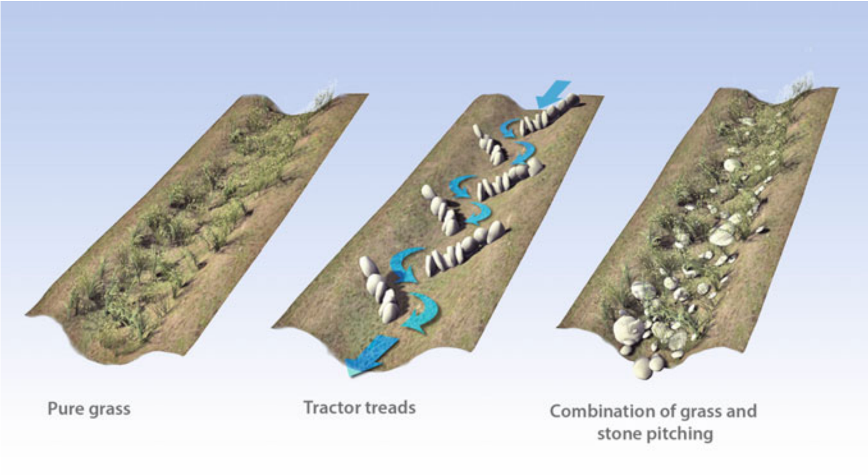


**Fig. 1** A silt trap division box. *Source* Pixiniti Studios

### 3.1.2 The Mini-Wetlands

The conventional practice is to convey runoff from waterways directly to the silt traps. The disadvantage of this practice is that there is no filtration of the silt and thus all the silt entrapped in the runoff end up in the silt trap. To avoid this, construction of a wetland could contribute to the filtration of runoff (DuPoldt et al. n.d). This ensures that the runoff discharge from the waterways is spread in the mini-wetland by reducing its velocity. As this happens, filtration of silt occurs—culminating in fairly clean water flowing into the silt trap. The efficiency of the system is thus improved given the clean water that is eventually harvested in the pond, especially if drip irrigation will be the choice of application.

### 3.1.3 The Automated Silt Trap

This is a new design for an off-stream silt trap that automatically conveys incoming and excess runoff into and out of the pond, respectively (Fig. 2). The size of the off-stream division box is influenced by the size and nature of water catchment in reference to soil type and vegetation cover, as well as the size of the pond. In the rural context where runoff is harvested via small roads and paths, a standardized size of 1.36 $m^3$ volume with a width of 1.22 m (approx. 4 ft), length of 1.83 m (approx. 6 ft) and depth of 0.61 m (approx. 2 ft) is currently in being researched on.

On the upstream side, the inlet for incoming runoff into the pond has a depth of 5 cm and length of 60 cm. The outlet from division box to the pond is 20 cm deep and 60 cm long, while the outlet from the division box to the downstream environmental flows has a depth of 10 cm and length of 60 cm. This is an automated

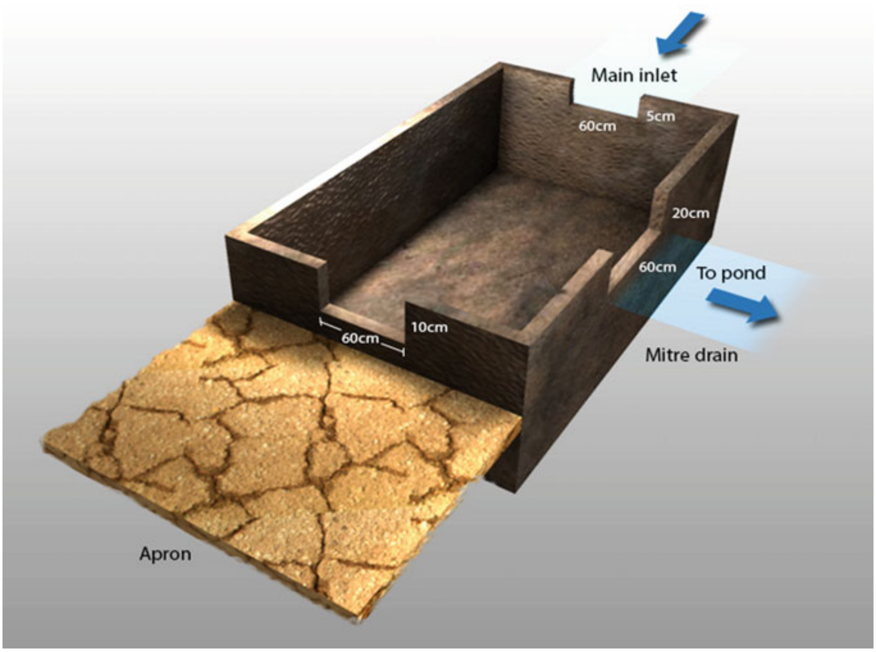


**Fig. 2** A silt trap division box. *Source* Pixiniti Studios

mechanism which ensures that runoff entering the silt trap division box has to first go to the pond after leaving behind the entrapped silt. When the pond is full, excess water flows back to the silt trap and flows out to the downstream areas. On the downstream side of the division box, an apron is constructed to avoid erosion at the outlet.

## 3.2 *Storage Mechanisms*

Concerns about efficiency of the reservoir component refer to storage capacity, losses due to seepage and losses due to evaporation. Quite often, storage capacity is decided upon based on availability of financial, local materials and/or labour resources rather than being linked to the crop water demand for full or supplementary irrigation. This is also influenced by the fact that the capacity from the catchments is more than adequate. It is not a wonder that it takes one to two storms of rain for the ponds to be filled up, allowing for cascading systems or downstream users to also benefit. In terms of storage, an efficient pond adequately meets the supplementary crop water demand. The best way to determine the size of pond is depicted in the examples presented in Tables 1 and 2 using either the double mass curve analysis (DOMCA) or the virtual water analysis:

**Table 1** Double mass curve analysis table for determining the size of a pond

| Parameter | April | May | June | July | August | September | October | November | December | January | February | March |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall (mm) | 340 | 214 | 88 | 4 | 0 | 0 | 213 | 112 | 22 | 11 | 0 | 12 |
| Total road area ($m^2$) | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 |
| Probability of rainfall occurrence | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| Runoff coefficient | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 |
| Monthly water supply | 1150.4 | 246.2 | 101.2 | 4.6 | 0.0 | 0.0 | 245.0 | 128.8 | 25.3 | 12.7 | 0.0 | 13.8 |
| Evaporation losses | 0.6 | 0.8 | 1 | 1.2 | 1.2 | 1.2 | 0.8 | 1 | 1.2 | 0.6 | 0.6 | 0.6 |
| Cumulative evaporative losses | 0.6 | 1.4 | 2.4 | 3.6 | 4.8 | 6 | 6.8 | 7.8 | 9 | 9.6 | 10.2 | 10.8 |
| Cumulative water supply | 1150 | 1395 | 141,176 | 141,177 | 141,172 | 141,166 | 141,405 | 141,526 | 141,542 | 141,545 | 141,535 | 141,538 |
| Monthly water demand | 800 | 1000 | 980 | 0 | 0 | 0 | 745 | 500 | 122 | 0 | 0 | 0 |
| Cumulative water demand | 800 | 1800 | 2780 | 2780 | 2780 | 2780 | 3525 | 4025 | 4147 | 4147 | 4147 | 4147 |
| Reservoir size | 350 | −754 | −879 | 5 | 0 | 0 | −500 | −371 | −97 | 13 | 0 | 14 |

**Table 2** Virtual water analysis table for determining the size of a pond

| Parameter | Acreage | | |
|---|---|---|---|
| | Half acre | One acre | 2.5 acres |
| Area ($m^2$) | 2020 | 4040 | 10,059.6 |
| Seasonal rainfall (m) | 0.3 | 0.3 | 0.3 |
| In situ volume ($m^3$) | 606 | 1212 | 3017 |
| Effective supply volume (l) | 199,980 | 399,960 | 995,900.4 |
| Command area (Acres) | 2020 | 4040 | 10,059.6 |
| Ideal harvest (kg/bag) | 90 | 90 | 90 |
| Ideal harvest (Bags/acre) | 15 | 30 | 74.7 |
| Harvest/area (kg) | 1350 | 2700 | 6723 |
| Virtual water (l/kg) | 900 | 900 | 900 |
| Virtual water (l) | 1,215,000 | 2,430,000 | 6,050,700 |
| Shortfall/pond volume ($m^3$) | 1,015,020 | 2,030,040 | 6,050,700 |
| Evaporation losses ($m^3$) | 50.751 | 101.502 | 252.74 |
| Water for domestic use ($m^3$) | 50.751 | 101.502 | 252.74 |
| Total pond volume ($m^3$) | 203.004 | 406.008 | 1010.96 |
| Pond capacity rounded off ($m^3$) | 200 | 400 | 1000 |

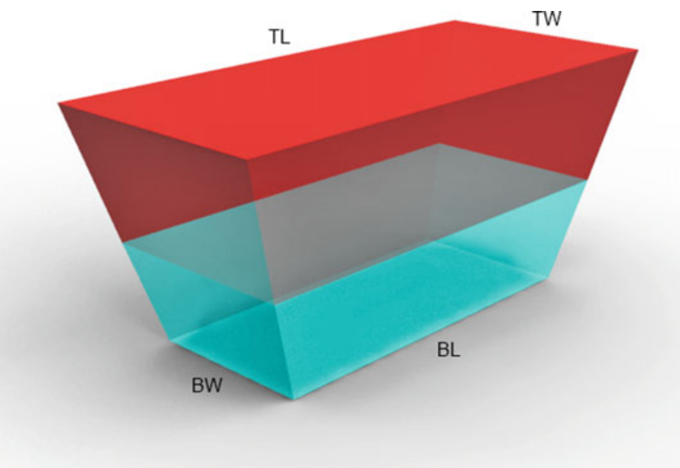


**Fig. 3** A schematic representation of a truncated pyramidal pond. *Source* Pixiniti Studios

After determining the volume using either Eqs. 2 or 3 below, it is then possible to carry out an iteration process in excel spreadsheet to establish the dimensions of the pond. The pond dimensions are clearly depicted in Fig. 3. The idea is to try and have a reservoir with depths more than 4 m. Deep ponds already provide room to account for evaporation losses, which are catered for when using the DOMCA approach.

$$V = 1/3\left((\mathrm{A1} + \mathrm{A2}) + (\mathrm{A1} * \mathrm{A2})^{1/2}\right) * h \quad (2)$$

$$V = 1/6(2 * \mathrm{TL} * \mathrm{TW} + \mathrm{TL} * \mathrm{BW} + \mathrm{TW} * \mathrm{BL} + 2\mathrm{BL} * \mathrm{BW}) * h \quad (3)$$

where

- $V$ = Volume of the pond ($m^3$)
- TL = Top length of the surface water body when the pond is full (m)
- TW = Top width of the surface water body when the pond is full (m)
- BL = Bottom length (m)
- BW = Bottom width (m)
- $H$ = Height of the water level (m)

The next concern is that of open evaporation. Data on evaporation of surface water bodies is available from open sources or the local meteorological stations. It would also be helpful to source for base maps of evaporation for the area in question.

With depths taken care of, widths should also be considered. Widths of ponds should be narrow enough to allow for the cost-effective incorporation of roof trusses that will enable roofing using iron sheets, shade nets, passion fruits or any other local materials such as sisal stems. The advantage of roofing using iron sheets is that the worry of children drowning in the pond is eliminated (Fig. 4). However, roofing of the pond using iron sheets is expensive compared to roofing using shade nets. For instance, a pond of 250 $m^3$ capacity with a roof surface area of 100 $m^2$ will need iron sheet roofing worth US$1000. On the contrary, the same area roofed using shade need will only cost US$80. The Kenya Rainwater Association (KRA) has been roofing using iron sheets but has now changed to using shade nets as the latter is cheaper in cost. ICRAF, AFRHINET, WFP and KRA under the auspices of the Billion Dollar Business Alliance for Rainwater harvesting have developed a protocol for assessing pond system. This is inclusive of the biophysical and socio-economic aspects.

**Fig. 4** A runoff pond covered with iron sheet. *Source* Pixiniti Studios

The efficiency of the runoff pond system due to covering of the pond is improved by the margin of water saved that would otherwise have evaporated. These are some of the aspects that will be monitored using the household runoff pond protocol application (HoPPA) currently being developed by the Billion Dollar Business Alliance for Rainwater Harvesting in Africa.

The other area of concern on storage is seepage. Ponds that are not lined can hardly last two weeks before water seeps and percolates underground. The efficiency of the runoff pond is thus greatly jeopardized when seepage occurs either following lack of lining or inserting a lining of poor quality. This is the reason why investing in an ideal lining material is worthwhile. At the very minimum, the polyvinyl chloride (PVC) lining should be at least 0.8 mm thick. Alternatively, a high-density polyethylene (HDPE) or high-density polypropylene (HDPP) material of 0.75, 0.8 or 1.0 mm would suffice as a lining material.

## *3.3 Abstraction and Application Mechanisms*

Abstraction and application components often go together. There are occasions or a context that entails pumping water from the pond and applying it immediately on the farm. Indeed, all the techniques used described in this chapter utilize direct application of water after pumping despite the fact that there are opportunities to pressurize the head in order to efficiently operate sprinkler or drip irrigation.

Abstraction is one of the core areas of concern on how pumping water from the pond affects systems efficiency. There are so many techniques used in abstracting water from the pond. On the other hand, application component of the runoff pond system is not well utilized, resulting in loss of efficiency depending on the mode of irrigation. The pumping and application techniques are assessed individually in the paragraphs below.

### 3.3.1 The Bucket and Rope

The conventional practice is to use a bucket tied to a rope and pull the water upwards. This approach is not only tiring as well as inefficient in time management but also ends up in supplying low quantities of water per given time. Therefore, the irrigable area ends up being small in size in comparison to areas irrigated if other methods of abstraction, for example, rope-and-washer pump, hip pump, treadle pump and solar water pump were used.

### 3.3.2 The Rope-and-Washer Pump

The rope-and-washer pump is a rotary hand pump that was developed by the Chinese in ancient times and later improved by the Nicaraguans in the 1990s. Thereafter, other countries improvised it to tailor their local conditions and requirements. The advantage of the rope-and-washer pump is the fact that it is simple, easy to manufacture and maintain and thus affordable for low-income rural communities. The cost goes for between US$60 and US$100.

Rope-and-washer pump has an efficiency of 75–85% and only require a force of 50–100 N, discharging a continuous velocity of 1–2 $ms^{-1}$ at a flow rate of 70 l/min (Fig. 5). This is much better as compared to a pressure pump which would need a dynamic force of 100–1500 N, discharging an intermittent flow velocity of 0–0.4 $ms^{-1}$ Its disadvantage is the fact that it has very low-pressure heads. This, however, can be improved by adding another wheel to enhance the mechanical advantage.

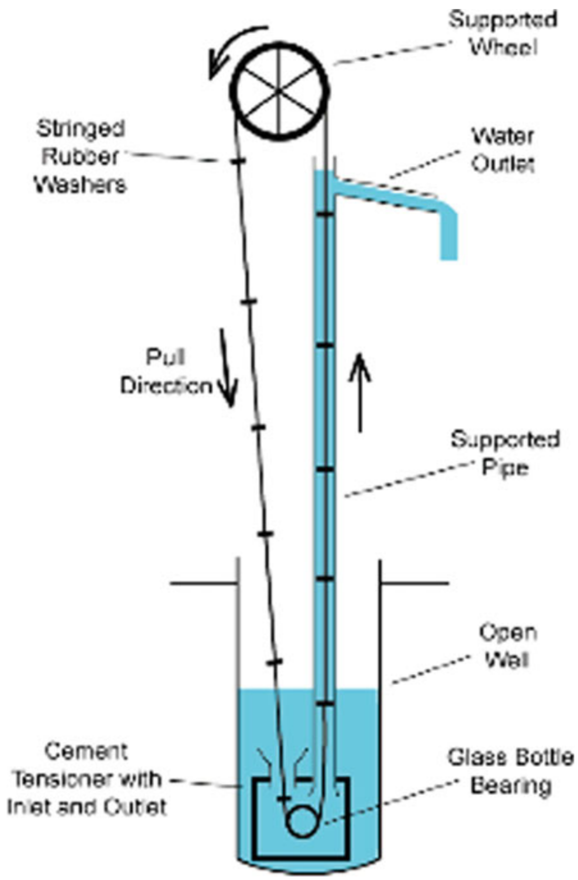


**Fig. 5** The rope-and-washer pump. *Source* http://www.hydratelife.org

The conventional practice for irrigation using the rope-and-washer pump is that water abstracted from the pond is applied directly to the fields through a hosepipe. This is inefficient given the fact that the application is not uniform. In addition, the force of large water drops causes erosion around the planting spots.

However, by adding an extra pulley, it is possible to pump water to an above ground tank. This increases the pressure head that will make it possible to operate both sprinkler and drip irrigation. The efficiency of rope-and-washer pump can also be improved by adding an empty plastic bottle to increase pressure head much in the same way as described in the use of the Brazilian case below.

### 3.3.3 The Brazilian Pump

The Brazilian pump is a modification of rope-and-washer, as well as the hip pumps. It forms an integral part of a complete water abstraction, conveyance and utilization mechanism. This pump can be operated through a pressurized (back and forth) or a crankshaft motion. The stroking movement of the Brazilian, rope-and-washer or hip pump, pulls the piston upwards thus creating a vacuum in the chamber that culminates in the suction of water from the reservoir along the inlet pipe. Just before this water is relayed to the delivery pipe, some of it–as well as some air–enters a 1.5 l plastic waste bottle. With continued cranking of the piston, more air is trapped. The result is a counter-pressure along the outlet pipe that culminates in the discharge of water to very high head/heights. Such pressure is adequate to operate a sprinkler irrigation appendage connected to the pump.

In comparison, the rope-and-washer pump requires more space and support stand unlike the Brazilian improvisation that occupies very tiny space (Fig. 6). There is, however, need to research on suction depths and maximum heads each of these pumps can attain.

### 3.3.4 The MoneyMaker Pumps

There are two types of MoneyMaker pumps. The first being the Super MoneyMaker pump and the second one is the Super MoneyMaker Plus pump. Both of these pumps are used to abstract water from surface water bodies such as wells, streams and ponds. The Super MoneyMaker pump has twin cylinders and works best for sprinkler and drip irrigation. It has a suction head of 7 m and a pumping head of 14 m above ground and can irrigate up to 0.8 hectares of land. The Super MoneyMaker Plus pump on the other hand is an improved version of the Super MoneyMaker pump as a response for simplicity and cost-effectiveness. Unlike its predecessor, it has one piston with the same suction and pumping heads. However, it can irrigate up to 0.4 hectares of land. This means that the Super MoneyMaker Pump is more efficient as it can serve twice the command area as the Super MoneyMaker Plus.

**Fig. 6** Brazilian hip pump with a plastic bottle assembly. *Photoraph* Alex Oduor

## 4 Conclusion

As a conclusion, the following actions need to be taken to improve efficiency of household runoff pond system along the component chain:

1. Construct wide (1 m wide) and shallow (30 cm deep) channels on both sides of a road and also along the waterways towards the silt trap. Vegetate these channels with grass and whenever possible, stone pitch the channels to reinforce and protect them from erosion. If allowable, let farmers owning land adjacent to the roads plant trees. Part of the runoff from the road channels could be directed to the trees via mitre drains. These actions will contribute to the reduction of siltation which will later improve on irrigation efficiencies—especially if drip irrigation is to be used.
2. Just before runoff along the waterways is conveyed to the silt traps, it should pass via a mini-wetland so that most of the silt is sieved. This way, a lot of silts are retained in the wetlands instead of being conveyed to the pond. Again, this improves the water quality necessary for efficient irrigation. The silt trap itself should be automated by varying the inlet, pond outlet and downstream outlet in a manner that it acts as a spillway. It should also be positioned off-stream so that

silt is not directly washed into the pond. All these are acts of improving water quality for efficient irrigation.

3. The pond should be able to retain as much of the water that was caught as possible. This efficiency to conserve is what is crucial especially to mitigate dry spells. In order to attain this, the pond should be trapezoidal in shape so that it is stable; it should also have narrow widths and depths beyond 4 m to take care of evaporation losses, or it should be covered altogether using shade nets, iron sheets or sisal poles.
4. Use rope-and-washer pump with pulleys to take care of mechanical advantage. Also, add a plastic bottle appendage to increase on pressure head and a hoist a tank (1.5–2 m) above ground to increase pressure head that is necessary for enhancing irrigation efficiency.
5. If using pipes to irrigate, include a shower head so that water droplets do not cause soil capping or soil erosion—and thus loss of water. Also, use drip irrigation that is the most efficient in water conservation.

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# Low-Tech Irrigation Strategies for Smallholder Vegetable Farmers in Kenya

**Silke Stöber, Caroline Moraza, Lucas Zahl and Esther Kagai**

**Abstract** Climate change is making rainfall needed for horticultural production in Kenya more unreliable. Applied on-farm research and data from household panel surveys are collected within the framework of the interdisciplinary research project HORTINLEA, which stands for Horticultural Innovations and Learning for Improved Nutrition and Livelihood in East Africa. It is a research consortium of German, Kenyan, and Tanzanian universities and research institutes funded by the German Federal Ministry of Education and Research. Of 1232 surveyed smallholders, 87% perceive climate variability and change; 32% of major shocks experienced are weather-related often causing lower yields. Climate change adaptation is limited to incremental activities, such as crop portfolio changes. Transformative strategies, such as investing in micro-irrigation are rare. In this study, costs and benefits of climate-smart water management and its adoption potential are investigated. A subterranean micro-irrigation system has been constructed in Kenya from easily accessible materials (low-tech). Results indicate a water savings of 39–70% compared to watering can irrigation in vegetable production. Vegetable growth during dry spells, and the low-tech aspect attracted further smallholders to replicate this system.

**Keywords** Climate change adaptation · Low-tech micro-irrigation
Resource-smart water management

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## 1 Introduction

The majority of Kenyan agricultural production is gained through smallholder farmers with an average farm size of 0.2–3 ha (World Bank and CIAT 2015). Domestic food production is hence dependent on farmers who typically have a limited amount of resources to generate their products and are vulnerable to economic and climatic shocks (Dixon et al. 2004; Rapsomanikis 2014). Lack of information and income risk can be seen as main constraints for smallholders to adopt innovations and technologies (Rapsomanikis 2014), implying that adaptation strategies like irrigation on Kenyan smallholder farms remain neglected. With almost one-third of Kenya's 2014 gross domestic product (GDP) coming from agriculture (World Bank 2016), the sector can be considered an important backbone for Kenya's economy. Specifically, the horticultural sub-sector is of growing importance for the local economy (Weinberger et al. 2011; Maertens et al. 2012; Njenga 2015). Kenya's horticultural sector can be identified as an important provider of livelihood for smallholders and furthermore a key driver for realization of the country's "Vision 2030" development goals envisioning Kenya as a semi-industrialized middle income economy by 2030 (Njenga 2015). At the same time, only one-third of Kenya's total land area is considered productive for farming, with high potential farming areas with more than 2000 mm mean annual rainfall are scarce (Orodho 2006). Also, with less than 1000 $m^3$ per capita of annual renewable freshwater supplies, Kenya can be classified a water scarce country (UN 2014). Despite these challenges, much of Kenyan horticulture is operated on arid to semi-arid lands (Government of Kenya 2010).

Rainfed farming is not possible in these areas unless farmers resort to using rainwater harvesting or irrigation to grow crops. However, HORTINLEA household survey data conducted between 2014 and 2016 reveals that most Kenyan farmers ($n$ = 1232) do not use irrigation on their homesteads and agricultural plots (Table 1). Overall, 25% of the indigenous vegetable crops are irrigated, for exotic vegetables (spinach, tomato, cabbage, onion, carrot) the rate is slightly higher with

**Table 1** Overview of irrigation usage on plots of surveyed farms in Kenya

| Does the household use irrigation on the plot to grow these crops? | Plots with | | | | Total plots |
|---|---|---|---|---|---|
| | Other crops | Field crops | Exotic vegetables | Indigenous vegetable | |
| No | 40<br>75.47% | 2532<br>87.73% | 458<br>64.15% | 2454<br>75.32% | 5484<br>79.35% |
| Yes | 13<br>24.53% | 354<br>12.27% | 256<br>35.85% | 804<br>24.68% | 1427<br>20.65% |
| Total | 53<br>100% | 2886<br>100% | 714<br>100% | 3258<br>100% | 6911[a]<br>100% |

*Source* HORTINLEA (2014)
[a]This total describes total plots of the 1232 surveyed households, i.e., there are 5.6 plots per household

36%. Generally, the use of watering cans and hosepipe sprinkler are most commonly used. Drip and furrow irrigation is very rare.

Wasteful technologies, poor management and maintenance, lack of human capacity as well as high investment costs have been jeopardizing the sustainability of irrigation schemes (Kenyan Ministry of Water and Irrigation 2009; Gichuki 2010). In this paper, the focus is put on a rainwater smart low-tech as well as low-cost irrigation strategy. It must be noted that such strategies are complementary solutions to dealing with water scarcity in agriculture. Rainwater harvesting for crop production is understood here as techniques of inducing, collecting, storing, and conserving local surface runoff for agricultural production (Siegert 1994; Rockström 2000).

Kenyan vegetable farmers are already subjected to challenges related to the naturally occurring seasonality of rainfall. Typically, the majority of precipitation occurs in the main rainy season from March to May (the "Long Rains") and a less intense period from October to December (the "Short Rains") (Government of Kenya 2010). Climate change is expected to pose challenges to Kenyan agriculture, further exacerbating an already vulnerable situation, especially of smallholder farmers. The HORTINLEA panel household survey reveals that 87% of smallholder farmers perceive climate variability and change. Of these farmers, 46% perceive more and longer rains, while 29% perceive less and shorter rains, and 11% more erratic and extreme rainfall. Of the households surveyed in the sub-humid and semi-arid areas ($n$ = 424), 54% perceive less and shorter rains, only 14% more and longer rains, and 13% more erratic and extremes. This indicates a dichotomy between humid and drier regions, with a clear tendency of drier regions to dry up and wetter regions to become wetter. The following chart (Fig. 1) shows the perception of rainfall in the Kenyan counties and selected agro-climatic zones (ACZ) surveyed.

As a result of this, adaptation strategies achieving resilience to the repercussions of climate change while maintaining or even better enhancing productivity are direly needed. In fact specifically for the area around Kajiado County analysis of historical weather data shows that in the past temperatures have been rising, while the amount of annual precipitation has been declining. Figure 2 demonstrates this development from 1980 to 2012 based on weather data recorded by the operators of Jomo Kenyatta International Airport (JKIA), which is located very close to the border of Nairobi to Kajiado County.

Contrastingly, climate change forecasts for East Africa and Kenya seem to agree on an overall rise in temperature, the projections for precipitation are somewhat divergent (Niang et al. 2014). Nevertheless, farming in the region should take such chances of variability and volatility seriously due to farming's importance for feeding the population and fueling the economy. Smallholder's perceptions of experienced rainfall in the previous season reveal that those farming in humid counties, do not yet see it to be a constraining factor. For those farming in the sub-humid counties, the rate is a bit higher, while the in semi-arid county of Kajiado over 70% of the farmers' state there was too little rainfall. The chart below (Fig. 3) demonstrates how farmers experience rainfall in the counties surveyed.

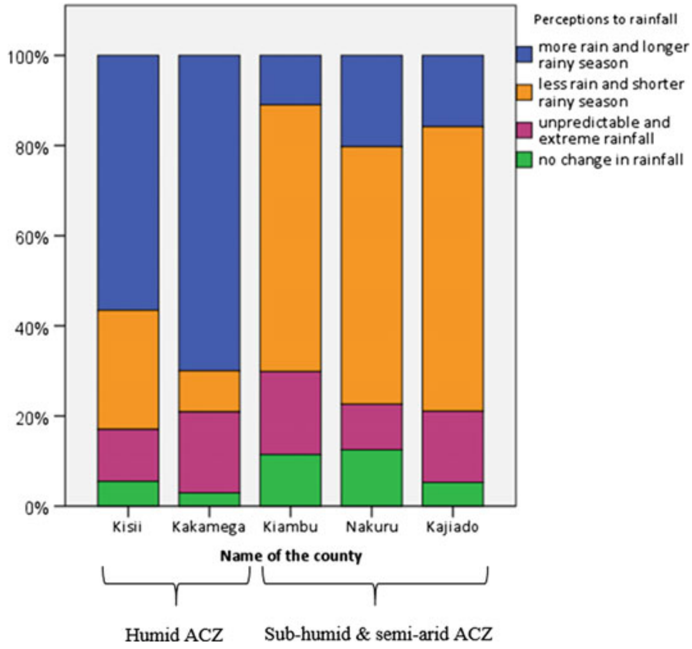


**Fig. 1** Farmer perceptions of rainfall. *Source* HORTINLEA (2014–2016)

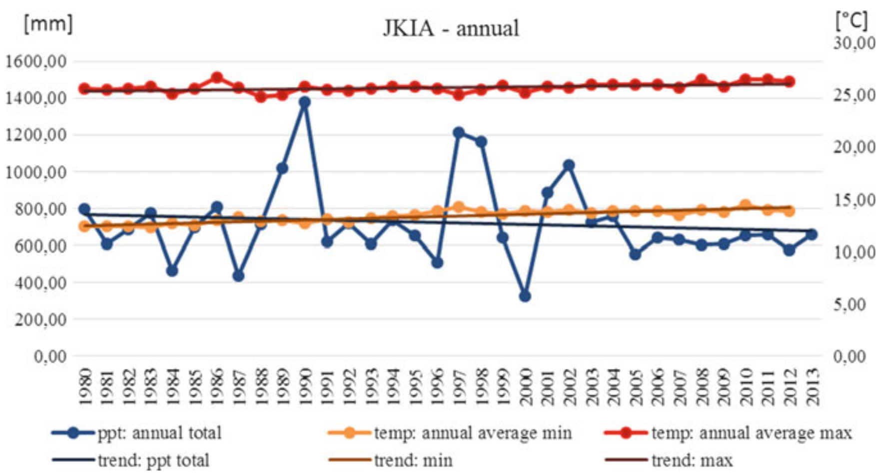


**Fig. 2** Weather development at JKIA from 1980 to 2012

Of the major shocks that vegetable smallholders experience during the previous year 32% are weather-related, i.e., drought, flood, heavy rain, or storm often causing crop failures. Most Kenyan smallholders surveyed adapt to climate

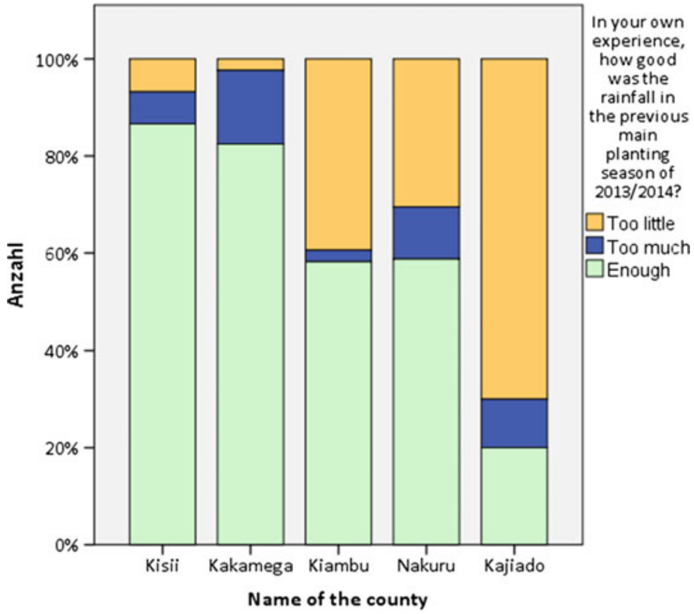


**Fig. 3** Experienced quality of rainfall in previous planting season. *Source* HORTINLEA (2014–2016)

variability and change by diversifying their crop portfolio, i.e., using other species. However, in the semi-arid county of Kajiado, households have claimed either they do not know how to adapt (52%) or they realize a need to invest in irrigation, dams, trees, and ponds (31%).

In this research, the increased rainfall unpredictability and variability is zoomed in on by further field research in Kajiado County. Although this means the results will be limited to and valid for a specific region, the expectation is that such results can prove to be indicators for similar circumstances in other areas of East Africa. The visited smallholder farms can be considered typical for Kenya as they lack access to perennial water sources and depend on rainwater for agricultural production. In Kajiado irrigation has become common, because vegetable production is no longer possible without irrigation. Unpredictable rainfall patterns call for adopting (rain) water smart management strategies sustainably exploiting locally available water. Smart water management strategies range from improving storage, irrigation, drainage, rainwater harvesting, and economizing water resources. Additionally, there is a need for application of good agronomic practices, next to efficient water utilization and harvesting to maximize agricultural productivity (Oguge and Oremo 2014). Strategies involving farm design such as agroforestry, terracing, swales, intercropping, mulching, companion cropping, and crop rotation can assist in becoming more water efficient. Ideally, rainwater supply is stretched to last throughout the drier season of the year enabling continuous production, fostering more economic and social stability for the producers. Rainwater harvesting strategies are not new to Kenyan communities with the technologies mostly being simple, acceptable, and replicable across diverse cultural and economic settings. Hence this assists their adoption and replicability (Ministry for Water Resources Management and Development n.d.).

The goals of this research are to understand what is already being done at the farm level to cope with water supply shortages and dry spells, and what innovative irrigation practices are attainable to achieve better on-farm water management. The inventory of farm-level practices leads to the following research question: (1) how do Kenyan smallholder vegetable farmers currently practice rainwater management in semi-arid regions?

As smallholder farmers typically have limited financial resources for investing in their farm, the cost of rainwater management and irrigation innovations should be kept low. Innovations should be easily understood by farmers and not require specialization or a large capital investment, thus the focus is on low-tech rainwater smart innovations. Therefore, to add more depth to this research, a low-tech/low-cost irrigation method is trialed at a farm in the town of Kiserian, Kajiado County. This leads to the second research question: (2) how does a selected low-tech irrigation practice perform (resource and cost efficiency) on the selected farm in Kenya?

Finally, it is important to also discover what factors of an innovation might motivate or hinder Kenyan smallholder farmers to adopt such rainwater smart management practices. Such information is valuable for designing and organizing the promotion of sustainable irrigation innovations. Therefore, the final research question is: (3) what motivates or hinders smallholder vegetable farmers in adopting rainwater smart management strategies?

## 2 Material and Methods

### *2.1 Study Area*

The farms surveyed for this research are located southwest of Nairobi in Kajiado County. One reason for choosing Kajiado is available panel survey data within the research project HORTINLEA and the prevalence of horticulture in these areas. This research focuses on selected smallholder subsistence and commercial farmers. The farms examined are mainly located in the northern part of Kajiado. Hence, they can be considered as peri-urban due to the proximity to the capital city. Figure 4 shows Kenya's ACZ as well as the locations of the farms surveyed within this research.

Kajiado County is located at the southern edge of the former Rift Valley Province, bordering Tanzania to the South. The county's population counts over 800,000 people, while it covers an area of about 21,000 km$^2$ experiencing an arid to

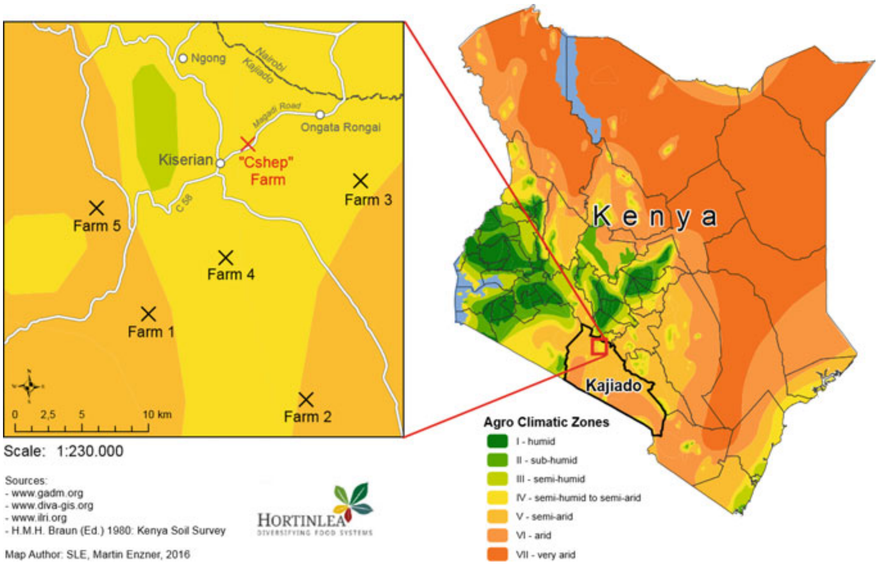


**Fig. 4** Location of farms observed in Kajiado (left) and ACZ of Kenya (right)

semi-arid climate with mean annual precipitation ranging from 300 to 800 mm (Boone 2007; Bobadoye et al. 2016). The county also has a bimodal rainfall pattern incorporating two distinct rainy seasons (Bekure 1991), with the average amount of rainfall decreasing when moving from the northern to southern parts of the county (Bobadoye et al. 2016). From this it is evident that the county endures a high level of temporal and spatial rainfall variability.

Like most Kenyan counties, Kajiado is confronted with scarcity of vital resources such as water and social amenities needed to enhance the economic and livelihood of its inhabitants (Chogo 2015). Most streams in Kajiado are seasonal and thus unreliable, while in parts of the county available groundwater has high salt levels (County Government of Kajiado n.d.). As an important resource for Kajiado's economic activities in cultivation and livestock rearing combined with a growing population, the demand for water in the county is growing rapidly and is estimated to be around 223,000 $m^3$ daily (Rutten 2005). Of this daily supply, 31,000 $m^3$ are needed for livestock, 8000 $m^3$ for wild animals, 15,000 $m^3$ for human consumption, and 170,000 $m^3$ for irrigation, however, boreholes, natural wells, and rivers only supply a daily maximum potential of 180,000 $m^3$, leading to a daily shortfall of 40,000 $m^3$ (ibid.). For this reason, strategies banking on rain-water harvesting are of great importance to help balance this deficit. In Kajiado, especially in its northern areas, with the help of irrigation horticulture has been gaining popularity, as rainfed farming proves to be unsustainable due to erratic rains (County Government of Kajiado n.d.). Nevertheless, unpredictability and unreliability of rainfall have had devastating effects on people's livelihoods, for example, in the drought year of 2009 crop failure in Kajiado was reported at more than 90%

while livestock losses were in excess of 70% in most areas (County Government of Kajiado n.d.).

## 2.2 Data Collection in Kenya

To receive an in-depth understanding of how smallholder vegetable farmers operate their farms and specifically manage their water resources, this research is grounded upon in-depth on-farm experience in Kenya from January to October 2016. The expectation from this is the ability to answer a wide scope of research questions, i.e., what rainwater management practices are used by Kenyan vegetable smallholder farmers, how a specific low-tech irrigation method perform for these smallholders and what might motivate or hinder uptake of rainwater smart farm practices. Within this specific research design, the data collection is based on on-farm investigations at five farms in Kajiado. This was mainly done with the help of semi-structured qualitative interviews and the drafting of farm profiles. Additionally, one specific low-tech irrigation method was tested on a case study farm.

The low-tech irrigation method is a subterranean micro-irrigation construction, which can be self-constructed from inexpensive as well as recycled materials. The construction is known as the "Green River Principle" (GRP) (Korrmann 2014). With the help of the on-farm trial the performance in crop production as well as its resource efficiency are examined. The data on the GRP's resource usage was collected during the dry season from May till October 2016 (May 14–October 24, 2016). The motivation for capturing the results in the dry season is to discover methods allowing for production throughout the whole year, hence enabling improved farmer livelihoods. The GRP was installed at the demonstration farm belonging to the Kenyan community-based organization "Community Sustainable Agriculture and Healthy Environmental Program" (CSHEP). This demonstration farm is approx. 25 km southwest of Nairobi in Kiserian, Kajiado County (Fig. 4).

Through CSHEP, it was possible to get in touch with various small-scale vegetable farmers in the area. Through interviews information was gathered on which on-farm water management and irrigation strategies farmers are using. Furthermore, they were asked to share their experiences and expectations in terms of water management in times of climate variability and change. The selection of smallholders was mainly based on the availability of contacts through CSHEP's network, functioning in the sense of a referral system, meaning one contact would lead to another contact. This data collection method in qualitative research can be described as snowball sampling, and it has the advantage of locating subjects appropriate for the study, while allowing for an introduction of the interviewer to populations which might otherwise be hard to get in touch with (Berg 2001; Noy 2008).

### 2.3 Green River Principle

The basic idea behind the GRP is to develop an irrigation system which is accessible for small-scale and subsistence farmers with low investment capacity, and thus often not able to afford conventional micro-irrigation systems like drip irrigation pipes. Making irrigation more accessible can assist in overcoming livelihood problems such as food insecurity, low income, and productivity. Three key criteria were considered for its design which guarantees the achievement of the previously mentioned problems. The first criterion is that the GRP is easy to understand and to build meaning adopters can easily reproduce it themselves and spread the knowledge to their community. One training can be enough to make people understand the idea behind and qualify them to train and instruct other people. With this knowledge, farmers should be able to adapt and further develop the GRP to their specific needs. The second criterion is to develop an irrigation system that recycles material, which are usually disposed of and be found all over the world. The GRP uses old plastic bottles, foil, and recycled newspaper, which can virtually be found nearly everywhere. Another benefit is that all these materials normally end up as waste causing pollution and creating problems for the community. With the GRP, the goal is to recycle resources, giving them a second life as something useful for the community and environment. All materials used to build the GRP are easy accessible in Kenya and can even be collected as scraps or as recycled material, which reduces the construction costs. The third criterion is to bring the investment cost for building such a micro-irrigation system to a level where even the poorest smallholder farmers can raise the amount needed. Due to the design and materials needed, the cost can be cut down to the absolute minimum. If farmers are willing to collect the materials second-hand and perform the necessary installation work themselves the costs will decrease even more. Finally, GRP has the benefit that it functions as a subterranean micro-irrigation system. Intense sunshine and erratic rainfall make such an underground system using minimal amounts of water, especially relevant for water scarce farming conditions.

To build the GRP only a flexible tube, plastic foil, plastic bottles, newspaper, and any type of water supply are needed. Ideally, the water being fed into the system is harvested rainwater, as was the case in this trial. For one row with a length of 10 m experience shows that around 100 bottles are required. The first step in building the GRP is to cut the base and head of used plastic bottles in order to connect them creating a main drainage pipe. The bottles used should ideally have a volume of one liter to guarantee enough space for water flow. The removed heads and bottle bases are cut into smaller scrap pieces and filled into the aforementioned main drainage pipe. This gives the main pipe more structure and prevents it from being squeezed or compacted after it is buried. Both ends of the main pipe need to be finished off with a bottle where only the base has been removed leaving the bottle neck and opening intact. Each pipe ending is then connected to a flexible tube. At the one end the pipe connects the system with the water storage supply, while the other one should after installation penetrate the ground enabling a source of ventilation.

The entire main drainage pipe made from plastic bottles must be perforated to guarantee water can consistently and evenly flow out throughout the length of the pipe. The next step is to cover the main drainage pipe with layers of plastic foil and newspaper. The pipe gets furled into a previously prepared sheet of plastic foil. This foil should be prepared as such that it is covered with newspapers and a thin layer of soil. This layer of newspaper and soil acts as a buffer preventing irrigation water from seeping to quickly through the main drainage pipe. The plastic foil is there to prevent that soil or crop roots grow into the drainage pipe causing blockage. Figure 5 presents a technical overview of the trench setup and the installed main drainage pipe of the GRP.

After construction the GRP is buried into the growing bed so that it can work as an underground crop irrigation source. The optimal growing bed length that the system can effectively irrigate has a length of 10 m like the system itself. If the constructed main drainage pipe length exceeds 10 m the system will lose stability and cannot be securely transplanted into its final position. By adding parallel rows the system can be extended to a bigger plot size. In fact the trial GRP system used for this research had a total of five rows. The total plot size under irrigation was 60 $m^2$. The growing bed rows should be kept at a width of 1 m apart, leaving a small path allowing for work on the vegetables. Furthermore the rows should be dug approx. 50 cm deep. The elected depth of 50 cm is chosen to ensure that the system is not damaged by tillage in the subsequent seasons, as the GRP should stay in the growing beds for a period of at least 5 years or longer. Before laying the drainage pipe down into the rows, the trenches should be lined with an additional plastic foil serving as a barrier between the irrigation pipe and the underground preventing water losses to deeper soil layers. After laying the pipe into the trench, the GRP should be covered with organic waste materials and at least 30 cm topsoil. For best results and to maximize efficiency the system should be adapted to the on-farm soil conditions. For example, in sandy soil a max depth of 30 cm is unproblematic. In case of soils with higher amounts of clay and silt the row depth

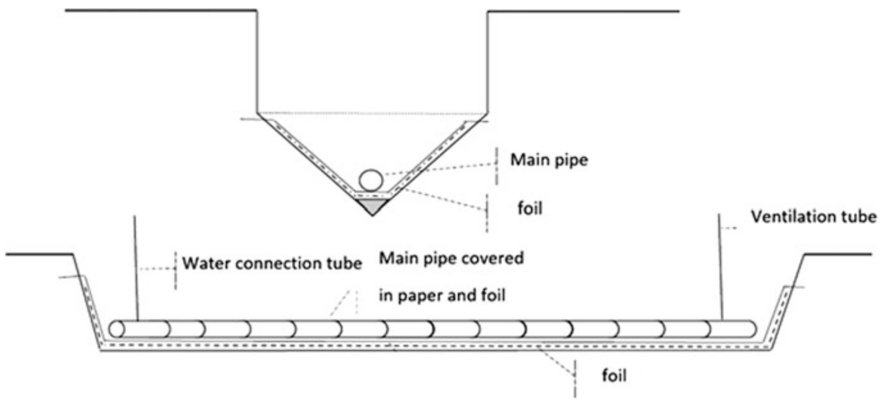


**Fig. 5** Technical overview of GRP drainage construction. *Source* Adapted from Korrmann (2014)

should be less in order to make it easier for the roots of planted crops to reach the system. The following graphic (Fig. 6) schematically shows the constructed GRP with water access, while Fig. 7 presents photographs of the different installation phases of the GRP.

## 3 Rainwater Management Methods Used in Kajiado

In the area around Kiserian, five small-scale farmers (Fig. 4) were visited and profiles of their farms, water management, and irrigation strategies were collected. Table 2 shows that all farmers use some form of micro-irrigation system. In most cases, this is with the help of water pipe drip irrigation. Furthermore, nearly all farmers were collecting rainwater with the help of roof catchments from where the collected water is stored in various storage facilities. The common practices for water storage are using tanks with a holding capacity of 5000–10,000 l. These tanks are comparatively cheap, easy to install, and have a long life expectancy. Also, more advanced storage facilities have been observed on the farms. Storage basins, which can also be used as fishponds, are a new technique to combine farm diversification, water management, and a multiple production cycle. Figure 8 provides photographs of the storage facilities found in Kajiado County.

## 4 Resource Efficiency of GRP

The GRP system trialed in Kiserian consists of five installed channels which irrigate a total plot size of 60 $m^2$. Per channel one growing bed with four crop rows can be applied and planted. To compare the efficiency of the GRP with common irrigation practices used by farmers a control plot of the same size is planted with the same crops. The soil type found at the trial farm is vertisol (locally known as "black cotton soil"). This soil typically has high expansive clay content that forms deep cracks during the dry season, while it adopts a very sticky texture when moist. This

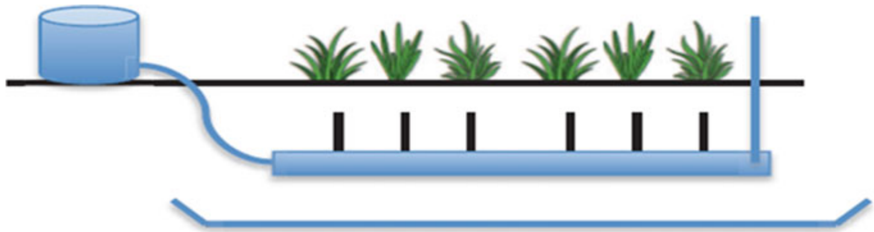

**Fig. 6** Schematic drawing of GRP setup. *Source* Korrmann (2014)

**Fig. 7** Step-by-step GRP construction phases. *Photos* Lucas Zahl

means the soil shrinks and swells depending on the amount of water it holds making it rather difficult to handle.

Normally, if crops are grown throughout the dry season (in this research: May 14–October 24, 2016) a common method used by smallholder vegetable farmers is to irrigate the crops with the help of a watering can. Irrigating with watering cans requires an ideal amount of 10 l water per crop row twice a week. This amounts to a weekly demand of 80 l water for each growing bed, meaning for a total of five growing beds 400 l of water are needed per week to irrigate the 60 $m^2$ plot area. This means for a dry season period of approx. 23 weeks ideally 9,200 l are available for irrigation ensuring crops will mature properly. However, rainwater storage losses resulting from a leaking storage tank made it inevitable to "borrow" water from a second storage tank, which is also in use for domestic consumption. This meant not enough water was available for an ideal amount of watering can irrigation. Hence, a less ideal amount of 5 l twice a week per crop row was applied. This amounted to a weekly water usage of 40 l for each, or 200 l for the five growing beds.Over the entire dry season this results in a total water use of 4,600 l with watering can irrigation. In contrast throughout the dry season the GRP system, equally consisting of five growing beds à four crop lines planted with the same crops, consumed a total of 2,800 l water achieving the same yield. Depending on the water availability when irrigating with watering cans, the GRP system can achieve an estimated water savings of 39% up to 70%.

In terms of resource efficiency, the GRP is a system that does not require special products that are solely designated for a GRP construction. The water tanks can be generic tanks meaning second-hand tanks are also feasible. The main drainage pipe can be built from used plastic bottles which would normally end up as waste.

**Table 2** Overview of observed irrigation and water management practices in Kajiado County

| | Interview partner (Name, Farmers Group) | Location (village, sub-county, county) | Water source | Water storage facilities | Irrigation system |
|---|---|---|---|---|---|
| Farmer 1 | Mary Nyankwar Maloba, Puan Farmers Group | Corner Baridi, Njoronyori, Ngong Sub-county, Kajiado County | –Community boreholes<br>–Rainwater harvesting from roofs | –Tanks<br>–Fishponds | –Water pipe drip irrigation<br>–Watering can irrigation<br>–Sprinkler irrigation |
| Farmer 2 | Edward Machanga, Nalepo Farmers Group | Nkorol, Ngong Sub-county, Kajiado County | –Natural spring<br>–Rainwater harvesting from roofs | –Tanks | –Water pipe drip irrigation<br>–Watering can irrigation<br>–Bottle drip irrigation |
| Farmer 3 | Maxwel Karasha, Kunda road Farmers Group | Kiserian, Ngong Sub-county, Kajiado County | –Community boreholes | –Tanks | –Water pipe drip irrigation<br>–Watering can irrigation |
| Farmer 4 | Pastor Peter Okeyo | Twala, Ngong Sub-county, Kajiado County | –Rainwater harvesting from roofs | –Tanks<br>–Storage basins | –Water pipe drip irrigation<br>–Watering can irrigation<br>–Furrow irrigation |
| Farmer 5 | Esther Kiruthi, Community Sustainable Agriculture and Healthy Environmental Program (CSHEP) | Kiserian, Ngong Sub-county, Kajiado County | –Rainwater harvesting from roofs | –Tanks<br>–Storage basin | –Bottle drip irrigation<br>–Watering can irrigation<br>–Subterranean micro-irrigation (Green River Principle) |

Furthermore, the buffer layer between the pipe and plastic foil can be made from old newspapers. Hence, there is no need to buy a special material exclusively designated for use in the GRP. The GRP has a life expectancy of at least five years and stays underground for this period. The benefit here is that after constructing the GRP, it can remain under the growing beds without requiring further maintenance. Because the system is buried deep enough it is protected from sunlight exposure, which increases life time. Also, it being underground reduces chances of breakage caused by tillage.

**Fig. 8** Different water harvesting methods found in Kajiado County. Photos: Lucas Zahl

## 5 Cost Efficiency of GRP

In our example at the CSHEP demonstration farm a total amount of 27,300 Kenyan Shilling (KES) was spent to set up the GRP system consisting of five rows with a length of 10 m and the potential to irrigate a plot area of 60 $m^2$. After applying the exchange rate this amounts to an expenditure of 220.10 €, as presented in Table 3. The bigger part of the money was spent on the pipes (2,800 KES), the five water storage tanks (5,400 KES), the plastic foil (6,950 KES), and the hired labor

(5,200 KES). All these costs can be cut down if the farmer is willing to collect the materials on his own, however, this may take longer. By direct connecting to an on-farm water supply or main storage tank the costs for acquiring a special tank can be avoided. Except from buying new plastic foil, the other components can be purchased second-hand or they are even items already available at the farm and can be re-used. Also, the required plastic bottles for the main drainage pipe can be easily collected from local streets, where they frequently end up as unmanaged waste.

When the investment costs are contrasted against the amount of harvested and sold crops gained in one dry season growing period the cost efficiency of the system is considerable. During the growing period, different African indigenous vegetables were planted and sold at farm gate. The crops were *Corchorus olitorius* (Engl.: Jute mallow, Swahili: mrenda) (28 bunches harvested), *Coriandrum sativum* (Engl.: coriander, Swahili: dhania) (105 bunches harvested), *Brassica carinata* (Engl.: Ethiopian kale, Swahili: kanzira) (62 bunches harvested), *Crotalaria brevidens* (Engl.: slenderleaf, Swahili: mitoo) (41 bunches harvested), *Brassica oleracea* (Engl.: kale, Swahili: sukuma wiki) (115 bunches harvested). This resulted in a total yield of 351 bunches with a weight per bunch between 0.25 and 0.5 kg, which could be sold for 20–30 KES per bunch. These sales generated a total income of 8070 KES in one dry season. Compared to our investment costs of 24,550 KES and an expected similar amount of yield in the coming seasons the breakeven point for the GRP is after approx. one and a half years (3 seasons). A breakeven can be achieved much earlier, in case the farmer would decrease the investment costs. This could be achieved by collecting instead of buying used materials like bottles and newspaper, avoiding the need to hire external labor, or using a larger single water supply instead of one tank per growing bed. With an assumed life expectancy of approx. five years the GRP offers a simple, cost-efficient, and resource conservative irrigation method that easily can be used as an adaptation strategy to difficult external climate conditions.

**Table 3** Overview of expenses for GRP system on 60 $m^2$ plot size

| Materials, services and consumables | Unit | No. of units | Cost/unit in KES | Total KES |
|---|---|---|---|---|
| Labor for construction | Hours | 26 | 200 | 5200 |
| Pipes | m | 10 | 280 | 2800 |
| Tanks | 100 l | 5 | 1080 | 5400 |
| Plastic Foil (50 m × 1 m) | Piece | 1 | 6950 | 6950 |
| Plastic bottles | Piece | 1000 | 3 | 3000 |
| Old newspaper | 10 kg | 2 | 600 | 1200 |
| Total | | | | 24,550 |
| in € | | | | 220.10[a] |

[a]111.54 KES = 1 EUR, exchange rate on March 28, 2016 retrieved from https://finance.yahoo.com/currency-converter/. Accessed Dec 19, 2016

## 6 Local Adoption of Rainwater Smart Management and Irrigation

In general, it could be observed that farmers are willing to test innovations and new technologies. However, the reported largest obstacle for installing an own low-tech irrigation system were the required investment costs. Further reported challenges are poor access to information and markets. Farmers claim that they often, if any at all, solely receive information on farming innovations from extension officers or neighbors. Another obstacle was the issue of not enough or too expensive trainings, poor networking, lack of formal education, and specialized knowledge. Moreover, challenges in being able to reach produce markets with large demand for (indigenous) vegetables or problems with post-harvest storage and processing were described. Such issues inhibit farmers' innovativeness as they are uncertain if they will achieve sufficient returns to reasonably invest in irrigation innovations. Finally, it must be noted that it also became evident that some farmers remain skeptical if rainwater harvesting and irrigation innovations can actually work for them. They emphasize that they would need a demonstration proving its functionality before they can be convinced. Nevertheless, after CSHEP offered trainings introducing the GRP, three smallholder farmers have autonomously adopted the system on their own farms.

## 7 Outlook

The farm structure in Kajiado County is family-based with small acreage, a low level of hired labor force and low investment in agricultural machinery, farm management and maintenance systems. Potentials are often not fully capitalized and investment strategies for a future orientation and positioning on the market do not exist. These circumstances impede adaptation and resilience to new challenges like the changing climate conditions. In general, the response of farmers to innovative techniques and methods is high and the majority is open to try them on their farms. If a method implies low investment costs, simple handling, and low maintenance effort; it has high chances to be accepted by farmer communities. The most frequent observed challenges of farmers in Kajiado are the unstable and changing weather conditions creating an enormous unreliability in planning, the hard work farmers face in their daily routine, and their unstable income situation influenced by market access and dependence on the weather. Resource efficient rainwater irrigation strategies like the GRP offer chances to confront these challenges. Although the GRP can theoretically be built to cater to any plot size, at this stage it is most suitable for irrigation of subsistence or semi-commercial gardens. By collecting more data on the GRP demonstration, its potential can be documented more precisely enabling a higher level of scientific relevance. In addition, limits of the system can be observed and adjusted to the local conditions. All in all, a new rainwater smart irrigation technique like the GRP will only be successfully integrated and spread in a community, when it takes the basic needs of small-scale and subsistence farmers into consideration. Only then stability of production and improvement of livelihood can become achievable. A follow-up trial should test a system which leads water through diverging pipes from, e.g., one 500-l water tank instead of five 100-l tanks. Additionally, the expenditures on the recycled materials (plastic bottles & newspaper) could be saved. A redesign using a locally manufactured 500-l water storage tank, which can be purchased at an original price of 4,600 KES, as well as collecting the recycled material could cut down the investment costs by approx. 20%.

During the rainy season, Kenya faces many problems related to heavy rainfalls causing environmental disasters such as negative impacts of erosion, landslides, and flooding. The large amounts of water that can be collected during the rainy season are in fact in demand for manifold uses, e.g., for domestic use, irrigation, and livestock rearing. A benefit of using rainwater is that it is much cheaper compared to relying on scarce conventional water supply systems. Technical solutions for a constant water supply like boreholes, abstraction from surface streams, deep wells, and dams need high investments for their construction and maintenance making them inefficient and less attractive for many small-scale and subsistence farmers. Another problem that Kenyan smallholders face is that the on-farm water storage capacity is on a very low to critical level, meaning large amounts for irrigation can barely be stored. In a water scarce country like Kenya to tackle such shortcomings the future goal should be to promote highly efficient rainwater management and irrigation strategies such as the GRP system combined with improved water harvesting and storage facilities on-farm.

Today locally organized community-based organizations (CBO) like CSHEP are among key players in on-farm trainings of farmers and spreading information. They play a major role in putting rainwater harvesting in the limelight on a local level. Cooperation with NGOs, churches, and government agencies helps lift local water problems to the attention of regional and national levels. In Kenya, agencies have conducted pilot projects and workshops to promote rainwater harvesting at national and local levels as well as support the development in the private sector. The latter is in fact a growing sector in Kenya and instrumental through local manufacturing of components that are needed to implement rainwater harvesting projects such as gutters, roofing material, concrete, and water tanks. Nowadays there are several local providers that make the materials for rainwater harvesting easily accessible in every part of the country.

Next to the importance of local organizations is the notion of farmer-led research. Such research working not for but closely with the farmer is an important way to ensure their inclusion. Farmers are often excluded from agricultural research taking place at institutions like universities, research institutes, or government offices. If they are included at all, often they solely act as providers of information or informants in surveys. Research performed in the field with smallholder farmers brings in fact many challenges as accounting or standardized record keeping are not very common. Nevertheless, close research with smallholders, who are one of the main stakeholders in food security and climate change adaptation, has the advantage of integrating them explicitly in the learning process, building research capacity, and increasing the potential to develop technically feasible and economically viable solutions that are trialed, evaluated and further adapted by smallholders themselves.

## 8 Conclusions

The analysis of the GRP trial demonstrates how attractive this system can be, as it is an innovative, low-tech and low-cost irrigation technique for small-scale, and subsistence to semi-commercial farmers in semi-arid ACZ. It combines a simple way of construction, which is easy to understand and single-handedly replicable with low investment costs, low maintenance requirements, and in the same time water-saving and protecting the environment. The opportunity to adapt the system to individual needs and conditions like soil type, plot size, etc., generates a wide potential of adaptive flexibility to the farmer. Another important innovative insight is to combine such a water-smart low-tech irrigation system with other agronomic practices that are preventive in terms of water loss. These are, for example, mulching, agroforestry, terracing, composting, crop rotation, and intercropping. A combination of these techniques together with rainwater harvesting can foster successful economic productivity. All these methods help tap the full potential of a farm and have comparatively low investment costs.

In future, Kenyan policy makers are challenged to develop and establish a micro-credit system that enables smallholder farmers to integrate low-tech and micro-irrigation systems on their farms. Another option would be an agricultural subsidy program fostering such methods of climate change adaptation in small-scale farming systems, hence helping resource-poor smallholder farmers to adequately adapt to climate variability and change.

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# Rainwater Harvesting Irrigation—A Strategic Measure for Integrated Rural Development in the Dry Mountainous Areas of Gansu Province, China

**Qiang Zhu and John Gould**

**Abstract** The loess plateau and hilly areas of Gansu Province are one of the driest areas of China. In the past, water scarcity caused domestic water supply insecurity, low levels of agricultural production, land degradation and impoverishment of the population. For many people, rainfall is the only practicable source of water. Since 1996, the rainwater harvesting (RWH) project has been used to provide supplementary irrigation. By 2005, formerly rainfed farmland irrigated using RWH systems totaled about 80,000 ha. An approach known as "low-rate irrigation (LORI)" has been developed in which irrigation is only applied at critical periods of crop growth. Highly efficient simplified irrigation methods developed locally along with drip systems have been widely adopted. Water application is targeted at the root zone to reduce evaporation loss. With only very small amounts of irrigation, crop yield has been raised by between 22–88% and 40% on average. Furthermore, RWH enables farmers to modify their agriculture patterns according to market needs. Farmers can now grow high-value cash crops, greatly decreasing poverty levels. Simple low-cost greenhouses have also been widely replicated, further boosting household incomes. The project, outlined in this chapter, has also benefited ecological restoration and the local environment as a whole.

**Keywords** Water scarcity · Rainwater harvesting · Low-rate irrigation
Water use efficiency · Poverty alleviation

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# 1 Introduction

The objective of this chapter is to give a comprehensive overview of the development of rainwater harvesting irrigation in Gansu Province, China, over the past 25 years. Many of the findings from field tests and research were undertaken by the Gansu Research Institute for Water Conservancy (GRIWAC). The large scale of the program and multiple investigations conducted over this period precludes the inclusion of details of specific experimental methodologies and results. A more detailed account of the whole RWH program in Gansu can be found in the book Every Last Drop (Zhu et al. 2012).

Rainwater harvesting (RWH) for supplemental irrigation has been practiced for at least 3000 years, and evidence of ancient systems from the Negev Desert in Israel has been documented in areas with mean annual rainfall as low as 100 mm (Evenari et al. 1961). India too has been the home of many ancient water harvesting systems (Agarwal and Narain 1997). China also has a very long history of using rainwater harvesting for both water supply and irrigation (Li et al. 2000).

Despite the long history of using RWH for supplementary irrigation and renewed interest in this approach in some parts of the world, there is a growing concern that opportunities for using this approach are being missed, especially in regions such as sub-Saharan Africa where food security issues are most acute (Rockström et al. 2007; Falkenmark and Rockstrom 2015). The urgent need to harvest and utilize more rainwater to address hunger and poverty also received considerable publicity following an announcement by prominent scientists at the 2014 World Water Week in Stockholm, (Falkenmark 2014). Preliminary investigations indicate significant potential for utilizing and managing rainwater better for improving agricultural production in Africa (Rockström and Falkenmark 2015) and in other semiarid regions. This makes the successful experiences with RWH in China, particularly relevant to demonstrating how they can enhance both food and water security globally (Zhu and Li 2003; Gould et al. 2014; Zhu et al. 2015).

China is ranked sixth largest in the world in terms of its total water resources. However, due to its huge population, the annual renewable water resources per capita is little more than 2000 $m^3$ which is less than a third of the global average and rank it 143rd out of 193 countries (UNESCO 2006). China is thus a country with some serious water shortages due to the uneven spatial and temporary distribution of water resources, especially in its arid interior (MWEP 1987).

Gansu, located in Northwestern China, is one of the driest and poorest provinces in the country (Fig. 1). The mean annual rainfall is only 280 mm, and the annual renewable water resources per capita are 1150 $m^3$, less than half of the national average. Water shortages have become an increasingly major restraint to agricultural production (Xu 2007). According to historical records, 749 droughts occurred over a period of 2155 years from 206 BC to 1949 AD, averaging about three droughts per decade. While in the 41 years from 1949 to 1990, there were 26 droughts or more than six per decade. The loess plateau and hilly areas in the middle and eastern part of Gansu Province suffered most (Yu et al. 1996). This part of the basin has an area of 107,800 $km^2$ and population of 17.7 million, of which 13.3 million are rural (GRIWAC 2005). In the loess plateau and hilly region, the average annual rainfall is about 440 mm and the annual renewable water resources are about 300 $m^3$ per capita (GRIWAC 2005). Although the Yellow River and its tributaries flow through this area, most of the land lies hundreds of meters above the river, so using this water for irrigation is very difficult. Another limitation is that the base flow in some tributaries has a high mineral content and cannot be used either for domestic purposes or irrigation. Groundwater sources are also frequently of poor quality and often located at depths of hundreds of meters (GRIWAC 2005; Zhu et al. 2012, 2015). The plateau is also crisscrossed with numerous gullies and ravines, which makes building canals and pipelines difficult. More than 80% of cropland is rainfed (GRIWAC 2005). However, the rainfall distribution is unfavorable to crop growth as the rainfall in May and June, when the crops need the most water, accounts for only around 19–24% of the yearly total (Zhu et al. 2012). More than 65% of the rain falls at the end of the growing season in July to October period (Zhu et al. 2012). The sparse vegetation and the hilly topography cause serious soil erosion which can be as high as 5000–10,000 t/$km^2$/y, equivalent to a surface layer of 5–10 mm being stripped off annually, causing great loss of soil nutrients and land degradation (Zhu et al. 2012, 2015). Water scarcity has resulted in low agricultural productivity, mono-cultural agriculture, and widespread poverty. Low productivity has forced farmers to cultivate as much land as possible including on steep slopes, thus accelerating soil erosion and land degradation. Millions of people lacked easy access to water and many hours were wasted daily fetching water from rivers in deep valley bottoms. The only other option was to use water of poor quality from ponds shared with animals (GRIWAC 2005; Zhu et al. 2012).

To solve these problems, local farmers and water technicians put great effort into leveling the land by building terraces and contour strips and adopting the use of mulching, plastic sheeting, and modifying agricultural practices. Since 1970s,


**Fig. 1** Map of Gansu Province and the project area

corn has increasingly been planted instead of wheat, as it is better adapted to the low-rainfall conditions. All these measures have been effective in reducing soil erosion, retaining rainfall in the field, cutting soil evaporation loss, and to a certain extent raising crop yields. Nevertheless, the overall impact of these measures on improving agriculture productivity was relatively limited as the crops still suffered water shortages resulting in low yields (Zhu et al. 2012, 2015).

An example was terracing which was used as one of the principle measures against drought in the area. Figure 2 shows the terraces in Zhuanglang County. After terracing, much of the runoff was retained and soil erosion and the associated nutrient loss were significantly reduced. The yield of terraced land in a normal year was increased by 40–50% compared to un-terraced slopes (GSWCB 1994). However, the moisture captured in the soil mainly during the rainy season (July–September) can only be used for seeding in the following spring. Over this 6–7 month period, most of the moisture was lost by evaporation during dry weather so when sowing takes place soil moisture is usually too low for seed germination and survival of the young plants (GRIWAC 2002; Zhu et al. 2012). Since 1970, plastic sheeting has also been widely used in Gansu. A 3-year study found that with this method the crop yield could be increased by 20–30% (GRIWAC 2002).

Planting more corn to replace wheat is also an important measure in terms of raising the yield, as corn has a longer growing period and can use more of the natural rainfall in July and early August (GRIWAC 2002). Thus, corn yields more

**Fig. 2** Terrace land in the Zhuanglang County, given the name "Terrace County" by the State. *Photo* Qiang Zhu (2010)

than double that of wheat. However, water deficit in late May and June can cause significant loss in corn yield (GRIWAC 2002; Zhu et al. 2015).

Long-term studies have shown that water shortages in the critical growing periods of crops are the main cause for low productivity in this region (GRIWAC 2002; Zhu et al. 2012). It has long been known that May and June are the most critical period for both wheat and corn, and drought is common in this period. In May and June, wheat goes through the growing stages of jointing, booting, and heading, while corn goes through jointing, early flowering, and sprouting (Zhu et al. 2012). Analysis of the rainfall data from Huining Gauge and water demand for corn and wheat (Zhu et al. 2015) showed that the rainfall in May and June in a normal year accounts for only 11–12% of the yearly total. Meanwhile, the crop demand for wheat and corn in the same period is 75 and 34% of that for the whole growing season, respectively. The rainfall and estimated water demand and water deficit for wheat and corn in Huining County, Gansu, for different periods are listed in Table 1.

It can be seen from Table 1 that wheat and corn suffer water stress during most of the growing season, but the most significant water shortage is in June, which is the most critical growing period for both crops (GRIWAC 2002). From the above analysis, it can be concluded that water deficit always occurs in the critical crop-growing period. Thus, supplying crops with supplemental irrigation in this critical period is the most effective way to enhance the yield. The challenge was finding a suitable water source. One of the conventional approaches utilized has been to build inter-basin water transfer projects. These kinds of projects require a huge investment and have high operational and maintenance costs making them unaffordable to both local authorities and farmers. Furthermore, the loess plateau and hilly area are crisscrossed by numerous gullies, which make the construction of water conveyance systems very difficult. The environment is also not conducive to the building of such projects due to problems like ground subsidence and landslips (Zhu 2003).

Only in the mid-1990s, with the implementation of the 1-2-1 rainwater harvesting project did the community get access to a water source it could use for

**Table 1** Rainfall, water demand, and deficit of wheat and corn in different periods in Huining, Gansu

| Item | | Mar | Apr | May | Jun | Jul | Aug | Sept | Year |
|---|---|---|---|---|---|---|---|---|---|
| Mean rainfall mm | | 7.5 | 25.0 | 41.7 | 46.8 | 79.9 | 79.3 | 49.6 | 373 |
| Water demand mm | Wheat | 10 | 57 | 133 | 152 | 28 | | | 380 |
| | Corn | | 10 | 46 | 112 | 138 | 136 | 18 | 460 |
| Water deficit mm | Wheat | −2.5 | 32.0 | 91.3 | 105.2 | −51.9 | −69.3 | | |
| | Corn | | −15.0 | 4.3 | 65.2 | 58.1 | 56.7 | −31.6 | |

*Note* Negative number in "water deficit" means the monthly rainfall is larger than the crop water demand supplemental irrigation (Zhu and Li 2000; Zhu et al. 2012). The 1-2-1 project initially focused on addressing the severe domestic water shortages faced by a rural population. This was due to the absence of both surface and groundwater sources, leaving rainwater harvesting as the only viable water source. The 1-2-1 project provided households with one catchment area, two large subsurface tanks (20–30 $m^3$), and one irrigated plot. Within just 18 months, the project met its goal of providing about 1.2 million people with water. Tiled roofs and concrete-lined courtyards provided catchments, and traditional water cellars were upgraded for storing rainwater, ensuring a safe, reliable, and affordable domestic water source (Zhu and Li 2000; Zhu et al. 2012). At the same time, rainwater was used to irrigate small pieces of land for planting vegetables and fruit trees in order to improve the community's diet and to produce additional income (Zhu and Li 2000; Zhu et al. 2012). The most significant outcome of the 1-2-1 project was that for the first time, the local people and the authorities recognized the enormous value of rain, as the only potential and accessible water source in the region. Due to the success of the 1-2-1 Project, the Gansu Government decided to initiate the rainwater harvesting irrigation project in 1996 (Zhu and Li 2000, 2006).

## 2 Description of the RWH Irrigation Systems

The RWH irrigation system is composed of three parts, the catchment, the storage tank, and the irrigation equipment (Zhu et al. 2015).

### *2.1 The Rainwater Catchment*

Runoff from the catchment provides the water source for the RWH irrigation system. A catchment with an adequate area and high rainwater collection efficiency (RCE) will help to guarantee enough water for the system to meet demand. The catchments used in Gansu can be classified into three kinds: the surface of an existing structure, a natural slope, or a purposed-built catchment (Zhu et al. 2015).

If available, using the surface of an existing structure is the most economical solution. The most commonly used structures include: roofs, paved highways, courtyards, country roads, sport grounds (Zhu et al. 2015). While household roofs and courtyards are commonly used as catchments for domestic water supply, paved highways are widely used for collecting rainwater for irrigation and their RCE can be as high as 0.6–0.7 (Zhu et al. 2012).

Usually, there is a drainage ditch by the side of the highway that has already been constructed by the transport department. To divert the runoff from the highway to the tank, it only needs construction of a small dike and ditch (Zhu et al. 2015). Rural roads can also serve as a catchment but can only collect water for one or two tanks due to the low RCE of their earthen surface (Zhu et al. 2015).

In recent years, many thousands of simplified greenhouses have been built in this loess plateau region as a result of the development of RWH. The plastic-film greenhouse roof has a very high RCE. Roof runoff is generally stored in a water cellar to irrigate crops inside the greenhouse (Zhu et al. 2012). Figure 3 shows some of the different existing structures used for catchments.

In the past, people used the ground surface for collecting rainwater, but nowadays, it is seldom used as a catchment, as a compacted loess soil surface has a very low RCE ranging from 0.13–0.25 (Zhu et al. 2012). In places where crops are planted far from the nearest road, a purposed-built catchment can be constructed using impermeable materials like concrete, cement soil, or a plastic-film covering (Zhu et al. 2012, 2015). The most commonly used material is concrete with a thickness around 4 cm (Zhu et al. 2015). Figure 4 shows a concrete-lined catchment used for irrigating orchards in the Qin'an County.

## 2.2 *Rainwater Storage Tank*

In Gansu, a traditional underground tank with the local name of *Shuijiao* (water cellar) has long been used for rainwater storage. An underground tank has many advantages (Zhu et al. 2012, 2015), these include:

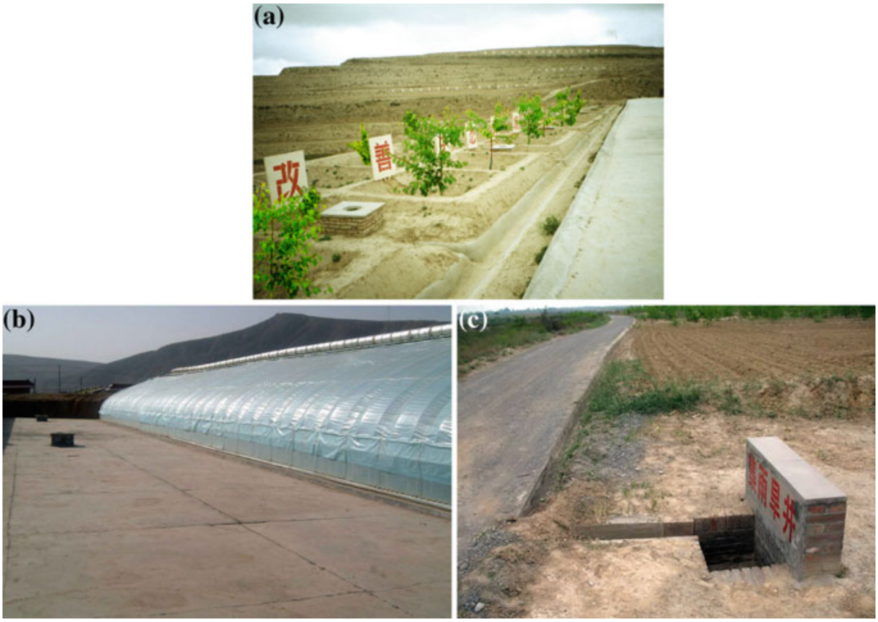


**Fig. 3** Existing structures used for catchments: **a** paved highway, **b** greenhouse roof, **c** country road. *Photo* Li Yuanhong (2000)

**Fig. 4** Concrete-lined catchment for irrigating orchards in Qin'an County. *Photo* Zhu (2003)

- Ease of collection of surface runoff
- Water quality can be maintained for a long time because of its low temperature and exclusion of all light by the tank cover
- Water remains unfrozen even in cold winters
- Reduces evaporation loss
- Reduced material requirements and cost as soil helps to stabilize the tank structure.

The water cellar can have a rectangular or circular cross section (Zhu et al. 2015). The circular design has a bottle shape with a volume ranging between 30 and 80 $m^3$ (Zhu et al. 2012). Depending on the soil properties, the circular water cellar consists of three distinct types, namely, the thin walled, the top domed, and the cylinder type. Of these, the most commonly used is the top-domed water cellar which has a bottom slab constructed with concrete and a 3 cm thick wall plastered with cement mortar, see Fig. 5. The rectangular underground tank can have a volume up to 1000 $m^3$. To keep the silt and debris out the runoff, water should first pass through a sediment basin, see Fig. 6.

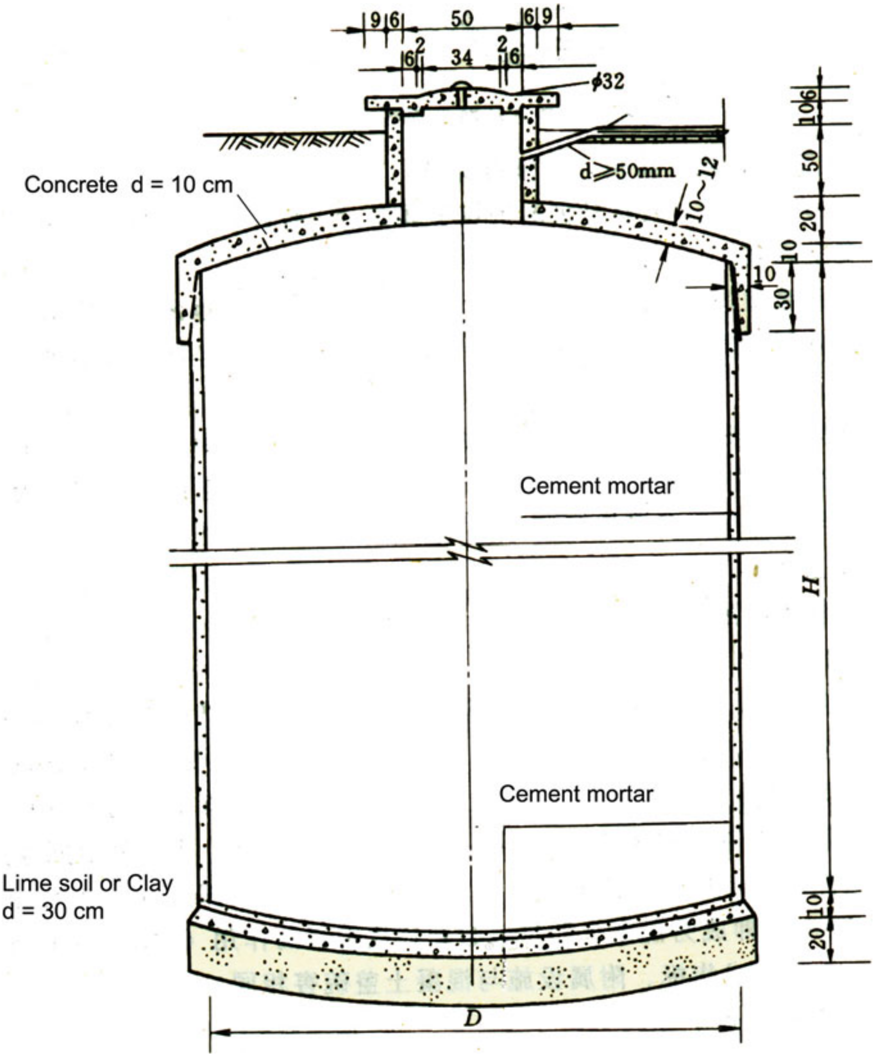


**Fig. 5** Illustration of a section of a domed water cellar

## *2.3 High-Efficiency Irrigation Equipment*

In Gansu, there are two kinds of RWH irrigation system: simple irrigation methods developed by local farmers and modern micro-irrigation methods mostly involving drip systems. The modern methods are used by the wealthier farmers with access to small loans from a bank or local cooperative (Zhu and Li 2000; Zhu et al. 2012, 2015). The locally developed simple irrigation methods include the following types as outlined below (Zhu and Li 2000; Zhu et al. 2012).

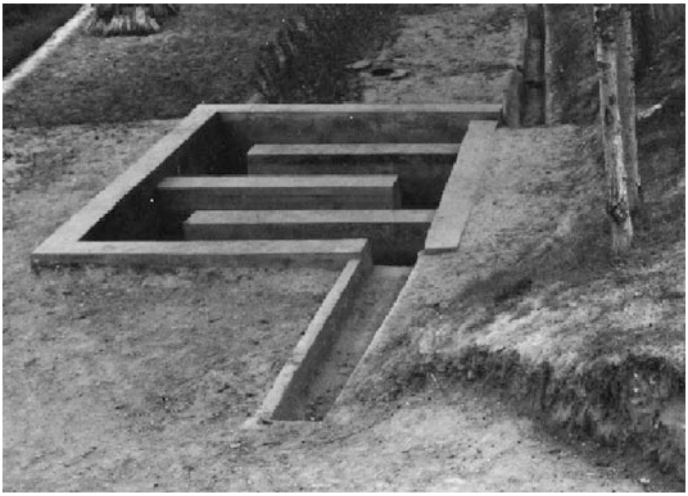

**Fig. 6** A photo of the sediment basin. *Photo* Li Yuanhong (2000)

(a) **Irrigation during seeding:** During sowing, a small amount of water (about one liter) is poured in the hole just before the seed is dropped in. Fertilizer may also be added at the same time, and the soil is then covered with plastic film. Although this operation can be done manually, integrated machinery has been developed to simultaneously undertake watering, seeding, fertilizing, laying the drip line, laying the plastic film, and compacting the soil (Cheng et al. 2009; Zhu et al. 2012, 2015). Irrigation during seeding uses only a small amount of water about 50–75 $m^3$/ha which can moisten the soil around a 25-cm-diameter zone surrounding the seeds. This can enhance the germination rate and help the healthy growth of young plants during a period of 30–40 days without rain (Cheng et al. 2009). Figure 7 shows an integrated machine for sowing and irrigation during seeding.

(b) **Irrigation through plastic sheeting:** After sowing, the soil is covered with plastic film. When the young seedlings emerge, cross-shaped cuts are made manually in the film to allow the plants grow and allow irrigation water and rainfall to flow in. Irrigation is done manually using a bucket or sometimes a hose from the tank, (Cheng et al. 2009; Zhu et al. 2012, 2015). Figure 8 shows the irrigation water being applied through the holes in the plastic sheeting.

This simple manual irrigation method is popular because it is low cost and easily managed. A bucket or hose is connected from the tank to water the crop root zone, see Fig. 9.

**Fig. 7** An integrated machine with a water tank mounted on a sowing machine for supplying a small amount of water in the seeding ditch. *Photo* Li Yuanhong (2000)

**Fig. 8** Illustration showing irrigation through holes in the plastic sheeting. *Photo* Xiaojuan Tang (2003)

(c) **Modern micro-irrigation methods:** Modern micro-irrigation methods include drip, micro-sprinkler, and bubble irrigation systems, of which the drip system is most commonly used for RWH irrigation in China (Cheng et al. 2009; Zhu et al. 2012). The micro-irrigation system is composed of three parts: the water source, the pivot, and the piping. In RWH irrigation, the water source is the

**Fig. 9** Manual irrigation using a hose connected to a rainwater tank. *Photo* Manjin Cheng (2009)

rainwater tank with a pump to produce pressurized flow (Zhu and Zhang 2001; Zhu et al. 2012). When the tank is located at a position high enough to produce the necessary pressure for the micro-irrigation, a pump is not needed. The pivot includes the valves, meters (water and pressure), fertilizer container (optional), and very importantly the filter. Since any silt settles at the bottom of the tank and due to the small scale of the system, a screen-type filter is used. The RWH-based pipe system includes the main pipe and the drip lines. To save costs, a movable drip system is used. After finishing irrigation, the whole drip system including the pump can be moved to another tank (Zhu and Zhang 2001; Zhu et al. 2012). Figure 10 shows an example of a drip system irrigation using rainwater.

**Fig. 10** Drip system using rainwater for irrigating corn. *Photo* Manjin Cheng (2009)

# 3 Enhancing Rainwater Irrigation Efficiency

Since stored rainwater is usually limited, its use in an efficient and beneficial way is the key to the success of any RWH irrigation project.

## *3.1 Development of the Low-Rate Irrigation (LORI) Approach*

With RWH-based irrigation in the loess area, a very low irrigation quota is used with each application. This ranges from between 50 and 225 $m^3$/ha, depending on the method used. The times of application are also limited. For grain crops (wheat and corn), irrigation usually takes place 2–3 times over the growing season: once during seeding followed by one or two further applications. Only when irrigating vegetables and fruit trees, water is applied more frequently (GBWR 1997; MWR 2001; Zhu et al. 2012). Investigations have shown that irrigation amounts for wheat, corn, millet, linseed, and potato amount to 225–400 $m^3$/ha using RWH-based methods, while for conventional irrigation 1500–2500 $m^3$/ha is required (GRIWAC 2002; Zhu et al. 2012).

Careful field tests have shown that these small amounts of water can be effective in enhancing crop yield. Demonstration projects have shown that yields of grain crops can be raised by 11–88% for wheat and 20–88% for corn. For each $m^3$ of rainwater used for irrigation, yields increase 1.7–3.9 kg for wheat and 3.1–5.7 kg for corn, respectively (GRIWAC 2002; Zhu et al. 2012).

This then raises the question of why RWH-based irrigation is so effective and efficient? Following long-term investigations and field testing, the GRIWAC developed a new approach to RWH irrigation called “low-rate irrigation” or LORI (Zhu et al. 2012). This involves using very small amounts of irrigation water at critical times and can significantly enhance crop yields. The current practices show that RWH irrigation only accounts for 10–15% of the crop water consumption over the whole growing season with regular rainfall providing the rest. The limited supplementary irrigation water from the RWH system just helps to tide the crop over periods of water stress during critical growth stages, thus avoiding serious crop damage. This maintains the crops health, so that later in the growing season natural rainfall can be used effectively (Zhu et al. 2012, 2015). Without this limited amount of water applied at critical periods, the crop would be damaged or wither completely. In this event, even if there were subsequent abundant rainfall, crop failure would be inevitable. The LORI water consists of natural rainfall that is stored and used at the most critical times. In Gansu, most RWH-irrigated land is still a form of rainfed agriculture dependent on in situ rainfall but supplemented with a further 10–15% of stored rainwater collected ex situ and applied at times when the crops need it most.

The LORI approach is based on the three following principles:

First, the adoption of a deficit irrigation approach to RWH irrigation; water stored in the tank is applied only at the critical periods of crop growth when it is most sensitive to water stress (Zhu and Li 2004; Zhu et al. 2012). The critical periods for crops vary with different climatic and soil conditions and can be identified from field experiments or by consulting with local farmers (GRIWAC 2002).

Second, the amount applied should be appropriate to get a higher water supply efficiency (WSE) and water use efficiency (WUE). The WSE is the crop yield increase as compared to pure rainfed production divided by the total irrigation water applied, and the WUE is the crop yield divided by the total crop water consumption including rainfall, soil moisture, and supplementary irrigation. While higher water application may produce a higher yield per unit area, it may not produce a higher WSE and WUE (Zhu et al. 2012; GRIWAC 2002). Obviously, in the loess area of Gansu where water for agriculture is limited but land is abundant, a prudent rainwater management strategy should endeavor to increase the WSE.

Third, reducing the evaporation loss can raise the rainwater irrigation efficiency. To achieve this, irrigation methods that apply water only to the crop root zone should be adopted. When irrigating, only a small part of soil around the plant needs to be moistened. Another measure for reducing evaporation loss is the adoption of plastic sheeting (Zhu et al. 2012). The land is covered with plastic film in the growing stages, and drip lines are usually installed under the plastic to reduce evaporation loss (GRIWAC 2002; Zhu et al. 2012). Figure 11 shows plastic sheeting and the covered drip line.

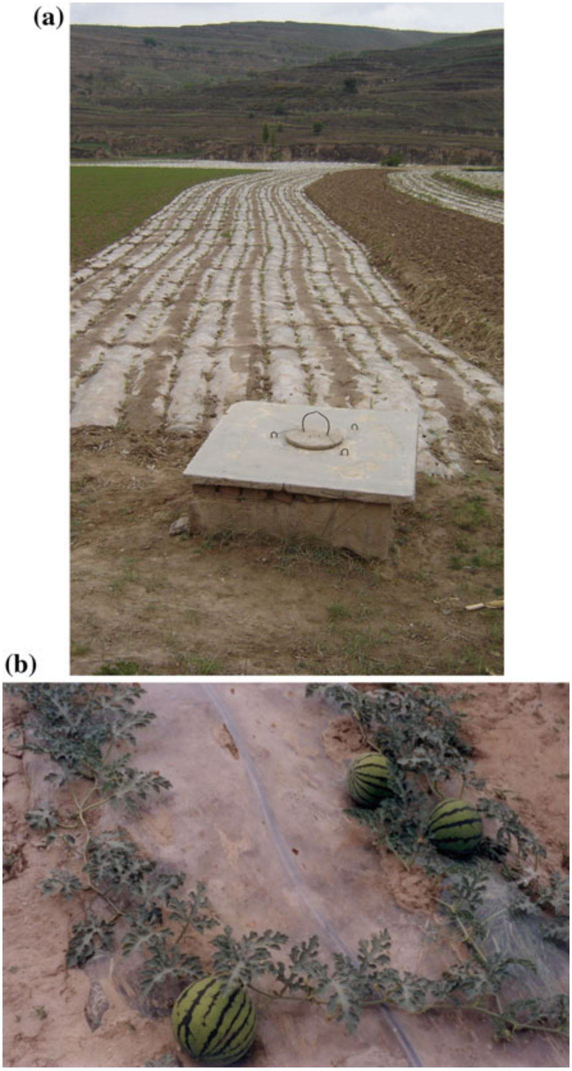

**Fig. 11** Plastic sheeting in Gansu **a** Plastic-sheeted field and water cellar, **b** Sheeted drip line for melon irrigation. *Photos* Li Yuanhong and Ziyong Huang (2000)

## 3.2 Modified Agricultural Practice

Before the RWH irrigation project started, more than 97% of the land had been planted with low-value cereal crops. Using rainwater stored in tanks for irrigation, farmers now grow a wide range of crops and adapt production according to the needs of the market, thereby greatly increasing their incomes (Zhu et al. 2012).

Tests have shown that supplementary irrigation with rainwater can increase cereal yields by 1.5–2 kg per $m^3$ (GRIWAC 2002), worth an additional 3–4 CNY (US$0.46–0.62, *Exchange rate US$1 = 6.5 CNY, February, 2016, and used* *hereafter*). However, for growing vegetables and other cash crops, each $m^3$ of rainwater can generate with a value of 10 times than that of grain crops. For example, for each cubic meter of irrigation water, cucumbers and tomatoes in greenhouses would yield 29 kg valued at 58 CNY (US$8.9) and 38 kg valued at 76 CNY (US$11.7), respectively (GRIWAC 2002).

### *3.3 Role of Greenhouses in Enhancing the Benefits of RWH Irrigation Project*

Greenhouses have played an important role in enhancing the economic value of RWH irrigation. Before the RWH project, there were no greenhouses in this dry, mountainous area due to the lack of water. After the implementation of the RWH irrigation project, the use of low-cost greenhouses developed rapidly (Zhu and Li 2006; Zhu et al. 2012). By 2005, it was estimated that their number had reached about 100,000. Most of the greenhouses were simple and affordable. There are two kinds of greenhouses: the walled greenhouse with an earthen wall located on the northern side and the arch-shaped greenhouse without a back wall as shown in Fig. 12 (Zhu et al. 2012). The walled greenhouse is the most common, as it can be used in extremely cold regions, where the nighttime temperatures can drop to −20 °C. The greenhouse roof is made of plastic film with thickness of 0.15 mm supported by steel rods and sometimes intermixed with bamboo (Zhu et al. 2012). A greenhouse with an earthen wall costs about 7000 CNY (US$1080) in the early 2000s, but could yield produce valued at between 2000 and 4000 CNY (US$300–600) annually depending on the crop type and management, thereby providing an excellent return on the investment (Zhu and Li 2006; Zhu et al. 2012).

The plastic-film greenhouse roof also provides a very efficient rainwater catchment. Tests have shown that RCE can be as high as 0.88. In the Dingxi County, where the annual rainfall is about 400 mm, the runoff from the roof can supply 83–89% of the water required to irrigate a crop of vegetables (GRIWAC 2002). According to Guo (2010), the percentage of roof water accounted for 42.3% of the total water use of an average greenhouse. Figure 13 shows a typical group of greenhouses.

The greenhouse is not only used for planting annual crops but even for fruit trees. Nectarines grown by villagers of Liuping Township in the Qin'an County could be harvested 2 months earlier than those planted outside, thereby securing a premium price. This early production translated to a value of 100–150 CNY (US$15–23) per cubic meter of irrigated rainwater (Zhu et al. 2012). The same strategy was also used for growing watermelons in the winter. The price of 6 CNY/kg (US$0.92/kg) obtained for the melons was three times of the normal price (Zhu et al. 2012). In an interesting trial, conducted by Gansu Academy of Agriculture Sciences, Enoki and White Elf mushrooms were grown in a greenhouse using a very limited amount of water. Yields for Enoki mushrooms

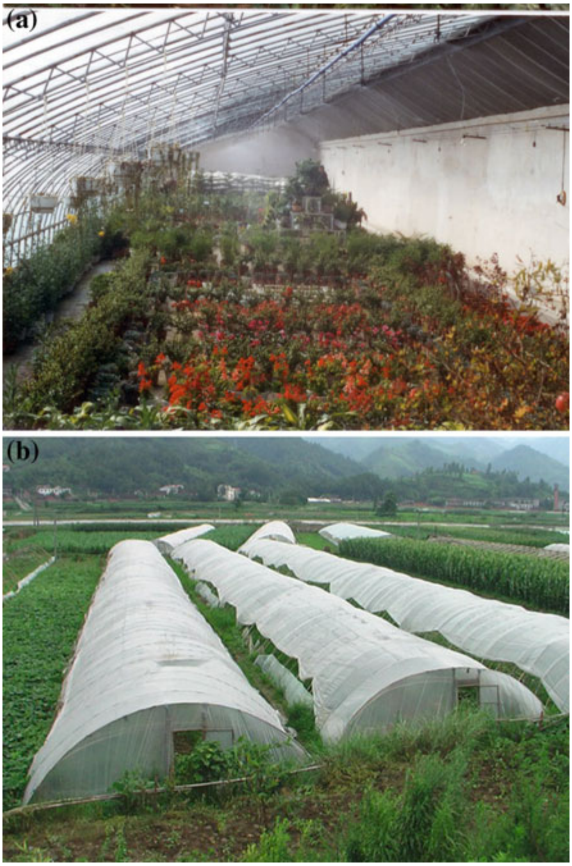


**Fig. 12** Simple greenhouses **a** solar-heated earth-walled greenhouse, **b** arch-type plastic tunnel greenhouse. *Photos* Ziyong Huang and Guo (2010)

(*Flammulina velutipes*) and White Elf mushrooms (*Pleurotus Nebrodensis)* amounted to 180,000 kg/ha and 108,000 kg/ha, respectively. The water use was only equivalent to 80 $m^3$/ha. The production value per unit of water used amounted to 14,625 and 40,500 CNY/$m^3$, (US\$2250/$m^3$ and US\$6230/$m^3$), respectively (GRIWAC 2002). Figure 14 shows the fruit trees and mushrooms being cultivated in the greenhouses.

# 4 Achievements and Challenges

## *4.1 Achievements*

An evaluation of the RWH irrigation project by GRIWAC (2005), reported that by the end of 2004, two million storage tanks had already been built. The project enabled about 80,000 ha of originally purely rainfed land to be irrigated using

**Fig. 13** Greenhouse group with tanks by the side of the greenhouses. *Source* Guo (2010)

stored rainwater (GRIWAC 2005). The main benefits from the RWH irrigation project included:

(a) Enhancement of yields by providing supplementary irrigation for crops that had previously been purely rainfed. Many farmers greatly increased food production. Mr. Luo Zhengjun in Luoma Village, Huining County, is a striking example. Luo's grain production increased by 270% after he built six water cellars with a capacity of 120 $m^3$, introduced plastic sheeting, and switched to growing corn instead of wheat (Zhu and Li 2003).

(b) Alleviation of poverty by diversifying agricultural production. With stored rainwater for supplementary irrigation, farmers were able to adjust their production and shifted away from mono-cultural grain production to more market-oriented crops. This has allowed them to grow vegetables, fruit trees, and even raise animals in their greenhouses, greatly increasing household incomes. The use of greenhouses and plastic sheeting has thus helped to rid this region of poverty and replace it with relative prosperity. The case of Mr. Bao Haiji from Zhengguo Chuan Village, Qingran Township, illustrates this point well, see Fig. 15. Before the RWH project, his village was one of the poorest villages, but by diverting runoff from a nearby highway and building nine rainwater tanks, Bao Haiji managed to boost farm yield and saved 160,000 CNY (US$24,615) within 10 years, a small fortune in the context of rural China (Zhu et al. 2012).

**Fig. 14** Photo showing **a** fruit trees, **b** mushroom growing in greenhouses. *Photos* Qiang Zhu (2010) and Li Yuanhong (2000)


(c) Improvement of the environment. With enhanced grain production and improved economic conditions, the trend of clearing more land for cultivation, even on steep slopes ceased. Instead, more and more farmers started to participate in the State initiated "Land Conversion" program that encouraged farmers to shift from crop cultivation on marginal sloping land to planting trees and grasses. These trees and pastures would then belong to the farmers, who got compensated with wheat and cash from the government for a period of 8–10 years. RWH irrigation helps to encourage the restoration of the environment in the region (Zhu et al. 2012).

(d) Creating an innovative approach to rainfed agriculture which enhances overall rainwater use efficiency. A key principle in rainfed agriculture is to enhance the WUE. This can be expressed as the output (either the amount or value of production) per unit of rainwater used. The practice of RWH irrigation includes retaining the in situ runoff in the soil and collecting and storing the ex situ runoff to irrigate crops when they need water most. Field trials have shown that by irrigating crops at the critical growing stages with limited amounts of stored rainwater, the overall WUE (kg/$m^3$) can be enhanced by 29–59% and 15–35% for wheat and corn, respectively (GRIWAC 2002).

**Fig. 15** Bao Haiji's **a** new house, **b** greenhouse, **c** corn field. *Photos* Xiaojuan Tang (2009)

## *4.2 Challenges Facing the RWH Irrigation Project*

The main challenge faced by the project is that many of the RWH tanks for irrigation are not being efficiently used. The reason is in part due to a miss-match between tank capacity and the size of their catchments. Some of the tanks receive insufficient runoff due to either inadequate catchment area or the low RCE of the catchment (GRIWAC 2005). Some technicians and farmers neglect the importance of ensuring a properly sized catchment to adequately supply the system. This is due to the poor awareness and lack of training of farmers and the agricultural extension service (Zhu et al. 2012). It is also not uncommon to find a rainwater tank full of water next to land that is not being irrigated. This is usually because of one or more of the following reasons (GRIWAC 2005; Zhu et al. 2012):

(a) Farmers are unaware of the benefits that RWH irrigation can offer as positive experiences have not been demonstrated to them.
(b) Suitable irrigation methods such as drip systems are considered unaffordable or economically too risky by poorer farmers.
(c) Farmers have been used to rainfed agricultural practices for generations and are unfamiliar with or lack know-how about RWH irrigation techniques.
(d) The above shortcomings are indicative of insufficient support from the agricultural extension services. Indeed compared to the 1990s and early 2000s, far less attention is being been given to RWH by the authorities. Due to rapid

economic development, more financial resources are now available to build large inter-basin water transfer irrigation projects and the focus has shifted away from small-scale initiatives such as RWH.

While it is true that a large project can provide irrigation to thousands of hectares, these are not appropriate in remote and mountainous areas, where people live in scattered settlements. Large irrigation projects can only supply water to discrete locations and along distinct corridors and those living far away from these locations miss out (Zhu 2003; Zhu et al. 2012). To help people living in remote and mountainous areas to farm efficiently and profitably, there is no choice but to use the only available water source which is—rainwater. Promotion of RWH should therefore remain a key responsibility of the authorities at various levels even while they devote themselves to larger projects.

## 5 Conclusions

1. RWH has now been practiced for small-scale supplementary irrigation for more than 25 years and has proved to be both cost-effective and popular with local communities, who have rapidly adopted it without any negative impacts on the environment (GRIWAC 2005). The RWH irrigation has been an important innovation for providing resilience against drought, ensuring food and water security, alleviating poverty, and conserving the environment. With the world facing a serious shortage of water, it is vital to consider not only using surface and groundwater but also to focus on the most basic water source that the Earth offers, the rain.
2. RWH irrigation is a special kind of irrigation appropriate in semiarid areas such as on the loess plateau of Gansu where conditions for agriculture are extremely adverse. This method uses only small amounts of water to enhance the overall efficiency of rainwater use in areas dependent on rainfed agriculture. In China, RWH systems are owned by individual households and compared to publicly owned or community-owned water storage facilities are highly efficient and have proved very effective in mitigating the impact of drought (Zhu et al. 2012).
3. Good management of RWH projects is the key to maximizing their potential benefits. Attention should be paid to help farmers, who are the owners of the systems to better manage them. This approach should include promoting awareness of the benefits of RWH irrigation, training and capacity building, as well as the provision of any necessary financial support such as affordable loans by local authorities.

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# Benefits and Challenges of Dugout Rainwater Harvesting Ponds in Tigray Region, Ethiopia

**Gebremedhin Berhane**

**Abstract** In Tigray, over 78,000 dugout ponds have been constructed since 2000. The objective was to alleviate the problem of recurrent drought that prevails in the region every five to ten years. However, it has been reported that most of the ponds are not functional. Therefore, this paper presents an assessment of the dugout pond construction in Tigray with a particular emphasis to challenges and technical problems and pinpoints the causes that led to the poor performance of the ponds. Thus, even though rainwater harvesting ponds have the potential to ensure availability of water for various uses and generate income for smallholders, poor performance levels and insufficient impacts to local communities were widely observed in the study area due to inadequate site selection, absence of biophysical survey during design and construction, leakage and evaporation losses, and poor management of the ponds.

**Keywords** Drought · Leakage · Plastic lining · Sustainability

## 1 Introduction

Subsistence rainfed agriculture is the mainstay of most African economies and contributes 10–70% to their GDP (Biazin et al. 2012). A safe, adequate and accessible water supply is a prerequisite for socio-economic development (Howard and Bartram 2003; RELMA 2003; Hunter et al. 2010; Koutsoyiannis 2011; IFAD 2012). It is estimated that by the year 2025, two-thirds of the world population will be living in areas facing water-stressed conditions (Ahmad 2002). The irrigation sector has expanded enormously over the past five decades enhancing agricultural production to meet world food demand (Ahmad 2002). Today, irrigation is practiced worldwide on about 260 million ha (Ahmad 2002). Irrigation is considered a key tool for agricultural development (FAO 1996; World Bank 2006). Although

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only 16% of the world's fields are irrigated, they yield 36% of global harvests (FAO 1996). In developing countries, irrigation increases yields of most crops by 100–400% (FAO 1996). Despite this, tens of millions of people in the Horn of Africa and East Asia currently suffer from hunger and are in need of food aid almost every year (IFAD 2011). This is particularly the case in Ethiopia (Ayenew 2003).

The main environmental challenge that Ethiopia and neighbouring countries are facing today is water scarcity and land degradation or erosion (Nyssen et al. 2002; Abdi et al. 2013; Berhane and Walraevens 2012; Adimassu et al. 2014; Tesfaye et al. 2014; Abrha and Simhadri 2015; Mekonnen et al. 2015a, b). Ethiopia has been severely affected by recurrent drought that prevailed almost every year (Biodiversity Newsletter 2003; World Bank 2006). The major droughts of 1985, 1991, 1992, 2000 and 2003, which claimed the lives of several thousands of people, have affected about 8, 7.3, 7.9, 10.6 and 14 million people, respectively, putting them under chronic food insecurity (NMSA 1996; Biodiversity Newsletter 2003). Though the shortage of rain is the major factor causing drought, the mismanagement and misuse of the natural resources, erratic nature of rainfall, soil degradation and population growth are major associated problems (Behailu and Haile 2002; Berhane et al. 2016). Irrigation is one means by which agricultural production can be increased to meet the growing food demand in Ethiopia (Awulachew et al. 2005). However, irrigated production is not satisfactory so far (MoWR 2002; Woldeab 2003). Shortage or irregular availability of water not only directly affects plant growth, but it may also prevent farmers from using costly inputs such as fertilizer and improved seeds (IFAD 2012; Wakeyo and Gardebroek 2013).

Rainfall in most of the arid and semi-arid regions of Ethiopia is not sufficient to support rainfed agriculture (Astatke et al. 1986a, b; Haregeweyn et al. 2006; Fekadu 2015; Berhane et al. 2016). Previous studies (e.g. Astatke et al. 1986a, b; Papavero 2004; Tilahun 2004; Gebrehiwot and van der Veen 2013) indicated that since the time of occurrence of rainy days varies irrigation and water conservation planning should be designed accordingly.

Therefore, it is extremely urgent to use the available water and land resources in a sustainable and equitable way. Surface water storage construction is one obvious choice to combat and alleviate the recurrent drought and avail water for the long dry period of a hydrological year which is common in arid and semi-arid regions. Even though water harvesting or pond construction is as old as human civilization, the use of optimization for design, procedures in site selection, construction and management of the pond system are a recent area of interest to geoscientists and engineers (Studer and Liniger 2013). Water harvesting is an ancient method of obtaining water that has received renewed interest in recent years as a viable water supply method for many regions (Frasier and Myers 1983), because of their simple design and low investment cost.

An attractive solution for resolving water scarcity in various parts of the world is the use of water harvesting systems for run-off water collection and storage (Oweis and Hachum 2006; Frot et al. 2008; Biazin et al. 2012; Studer and Liniger 2013). In northern part of Ethiopia, Tigray region, though agriculture plays an important role in the regional economy, crop production and productivity is limited due to various reasons (Haregeweyn et al. 2006; World Bank 2006; Berhane et al. 2016). Like in most part of Ethiopia, droughts, uneven and high intensity rainfall, rugged topography, lack of water resources management practice and poor or lack of experience in modern water harvesting techniques are some of the reasons for less agricultural production (Haregeweyn et al. 2006; Berhane et al. 2016). To alleviate these critical problems, massive construction of dugout ponds and other water harvesting structures (Haregeweyn et al. 2006) was launched by the Government of Tigray region in 2002.

This paper, therefore, intends to assess and evaluate the positive and negative impacts of the constructed dugout ponds since 2002 and the technical challenges faced during the planning, design and construction phases in arid and semi-arid regions considering Tigray as case study. Moreover, this chapter intends to provide basic information needed to design and construct a multiple-use pond in Tigray (northern Ethiopia) and other arid and semi-arid regions.

## 2 Methodology

### *2.1 Study Area*

The study area covers most part of Tigray regional state which includes the Tekeze River basin (Fig. 1). It covers 31 Woredas (i.e. districts) where most of which drain to the Tekeze River and finally to Blue Nile River. The study area is characterized by shortage of potable water and lack of water harvesting activities. Although significant progress has been made in the last few years, utilizing pond water for modern irrigation is still at its infant stage (Berhane et al. 2016).

Climatically, the study area is classified as arid and semi-arid regions (Gebreyohannes et al. 2010; Gebrehiwot and van der Veen 2013). The annual rainfall varies from 350 to 900 mm (northeast lowlands to southwest highland areas), and in most parts of the region, about 50–70% of the annual rainfall comes in the months of July and August only (Berhane 2002; Nyssen et al. 2005; Gebreyohannes et al. 2010). Estimates from the historical records of precipitation for the period 1954–2008 indicate that the mean annual rainfall is 560.7 mm (Gebrehiwot and van der Veen 2013). The rainfall shows highly intense showers up to 68 mm/h (Girmay 1995; Yazew 2005; Gebrehiwot and van der Veen 2013; Nyssen et al. 2014). Due to this rainfall condition, most of the rivers draining the area are dry or intermittent and the need for dugout pond or other water harvesting scheme construction is indispensable for a clear reason that water is needed for the longer dry period in arid and semi-arid regions. The mean annual temperature ranges between 16 and 38 °C, and the altitude varies from about 600 in the western lowlands to 3000 m a.s.l. in the highlands of Atsbi (northeast) (Gebreyohannes et al. 2010).

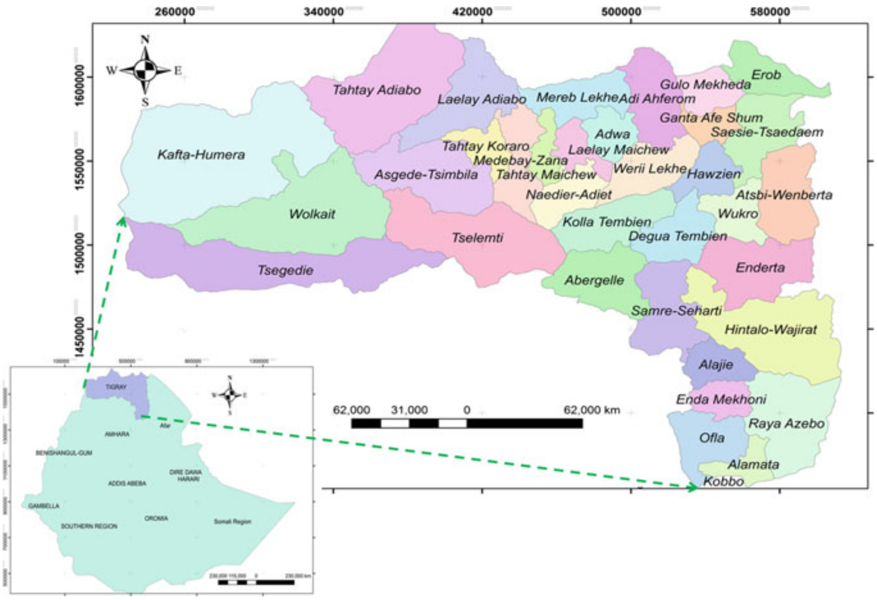


**Fig. 1** Location map of the study area (Tigray region)

Most streams and tributaries are controlled by geological structures and underlying geology (Nedaw and Walraevens 2009; Gebreyohannes et al. 2010). In 1970, Levitte studied the geology of northern Ethiopia in general and the central Tigray in particular, and he divided the rocks in the area into four major units: basement complex, sedimentary Palaeozoic–Mesozoic sequence, Cenozoic Trap Volcanics and Quaternary sediments (Levitte 1970; Beyth 1972). Berhane (2002) described the geology and structure of Mekelle area and its surrounding. According to this author, weathering, fracturing and geodynamic processes affect the hydraulic and engineering properties of the rocks.

## 2.2 Methods

The research work involved a number of fieldworks in different seasons (2002–2005 and 2007–2014). During the field surveys, three types of dugout rainwater harvesting ponds (clay blanket, cement and plastic-lined types) were surveyed in different localities of the region. Many dugout ponds were also visited during their construction period (2002–2005), while their performances (failure–success stories) were evaluated in the period between 2007 and 2014. In addition, many data were collected from regional organizations at the Woreda level (e.g. Regional and Woreda Water Bureaus). Generally, the study involved the following procedures (Fig. 2):

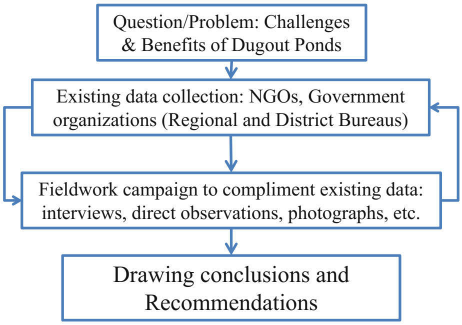


**Fig. 2** Simplified sketch showing the working procedure and flow

- Collection of existing data from different governmental and non-governmental organizations.
- Frequent fieldwork to collect actual data and observe existing conditions of the dugout ponds at different seasons.
- Some discussions and interviews were made with farmers who have dugout pond and with those who do not have.

Many discussions were also made with different professionals who participated in dugout pond design and construction and with those who did not participate.

Finally, all the data were synthesized, and the main challenges and technical problems faced during planning, design, implementation and management of the pond were pointed out and evaluated. Based on the outcome of the study, solutions to some of the problems and recommendations were forwarded. It is hoped that the observations, data and insights gathered from the case study will enable decision-makers and professionals involved in rainwater harvesting projects in the region and other similar regions with a better decisions regarding water harvesting techniques.

## 3 Results and Discussions

### *3.1 History of Pond Construction in the Region*

Most areas with low rainfall and/or with high rainfall but erratic distribution suffer from low and unstable crop yields (Tucker et al. 2014). Thus, the use of rainwater harvesting ponds for a lifesaving supplementary irrigation to rainfed crops is an alternative option (Hanjra et al. 2009) because of their low investment cost, manageable size and simple design.

Many people in Tigray/Ethiopia and throughout the Third World and arid and semi-arid regions (Hanjra et al. 2009; Biazin et al. 2012) lack access to adequate water supplies for household consumption, livestock and irrigation (Myers and Kent 2001; Oweis and Hachum 2006; Koutsoyiannis 2011). Ethiopia in general and

Tigray in particular face an enormous challenge in building the minimum platform of water infrastructure and management capacity needed to achieve water security (World Bank 2006). This condition exacerbates with little water resources infrastructure, weak management institutions and capacity, extreme hydrological variability and seasonality, and a highly vulnerable economy (World Bank 2006). Water shortages are particularly acute for small communities in rural areas which depend on the natural recharge of springs and wells (Astatke et al. 1986a, b). Frequently, such supplies are inadequate during the dry seasons (Astatke et al. 1986a, b). In suitable conditions, the problem can be alleviated by building ponds and other appropriate water harvesting structures which trap surface run-off during the rainy season for use later in the year (World Bank 2006).

The numbers of ponds constructed during the years 2002–2005 in 31 Woredas/districts of Tigray were estimated at around 78,000 from archives of regional and Woreda Water and Agriculture bureaus and inventory as presented in Fig. 3. The types of dugout pond distribution per Woreda (clay, plastic and cement lined) are presented in Figs. 4, 5 and 6. These ponds range in size from less than 64 $m^2$ to over 225 $m^2$ with a depth range of 2.5–4 m (average volume about 144 $m^3$) (Papavero 2004). Most of the ponds are dugout type with very few embankment pond types. Construction of ponds in the region was planned with aim that existing water supplies and irrigation can be supplemented by harvesting run-off water in excavated ponds, i.e. dugout ponds (Papavero 2004). Using simple construction

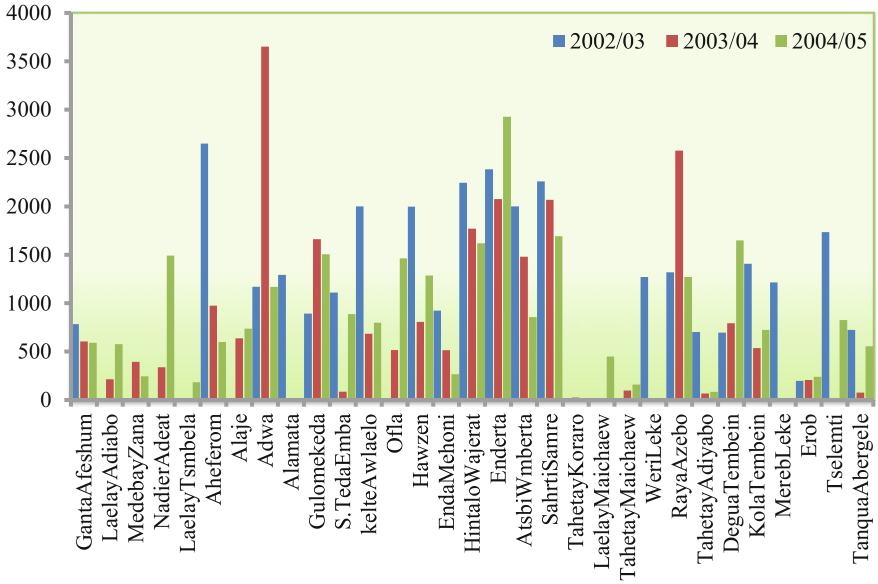


**Fig. 3** Total distribution of dugout pond construction in the years 2002–2005 per Woreda. *Source* Adapted from archives of regional and Woreda Water and Agriculture bureaus and present inventory

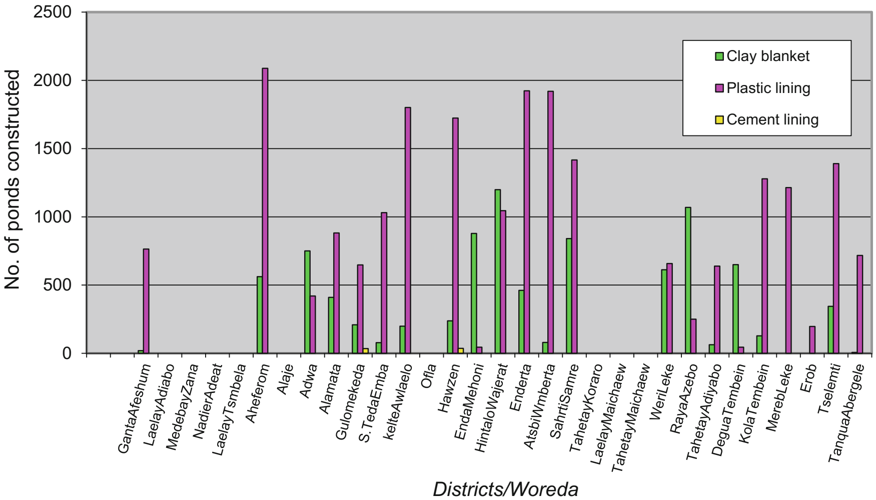


**Fig. 4** Pond construction type distribution in 2002/2003 per Woreda. *Source* Adapted from archives of regional and Woreda Water and Agriculture bureaus and present inventory

techniques and suitable materials, dugout pond can provide reliable sources of water (Papavero 2004; World Bank 2006) and offer the following advantages:

1. Community can be involved in the actual construction and develop sense of ownership, which they are more likely to maintain, and it is directed towards solving a problem of primary concern to rural dwellers.
2. The equipment needed is light and simple and thus suitable for use in remote areas.
3. The extension or technical skills necessary to design and supervise pond excavation are well within the capacity of the region at that stage of its development.
4. The construction techniques are easily taught to unskilled workers, thus cutting supervision time and cost.
5. With the exceptions of cement and synthetic plastic liner ponds (for some component of the pond), the necessary materials are usually locally available, making it one of the cheapest methods of pond construction in a rural community.
6. It requires little capital expenditure and makes minimal demands on the labour of individuals (since the workload can be shared by all the members of a village and household).

The constructed dugout ponds during the aforementioned years in the region are clay, plastic and cement lined. Usually, ponds are constructed for many purposes. These ponds were constructed mainly for two purposes: irrigation and domestic

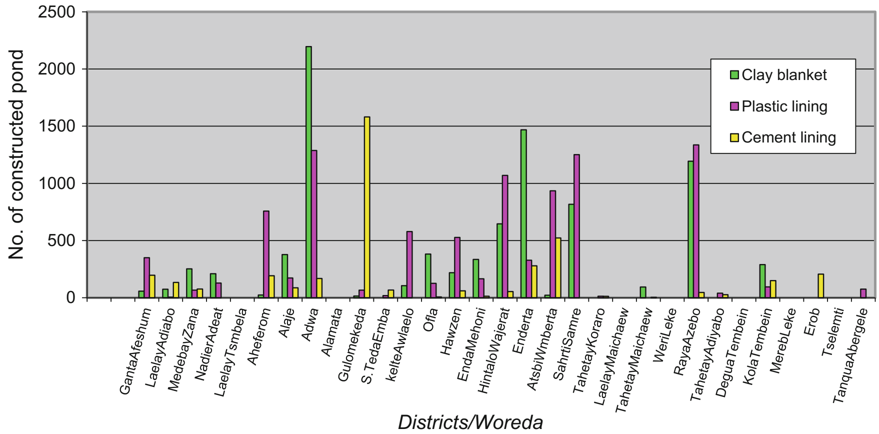


**Fig. 5** Pond construction type distribution in 2003/2004 per Woreda. *Source* Adapted from archives of regional and Woreda Water and Agriculture bureaus and present inventory

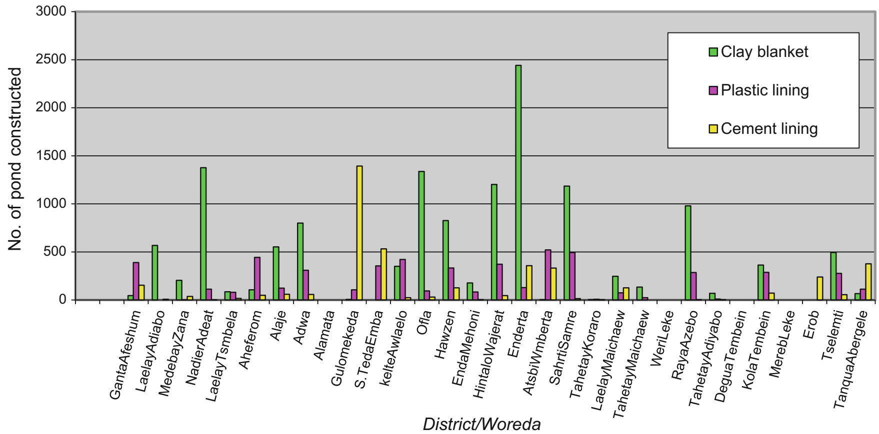


**Fig. 6** Pond construction type distribution in 2004/2005 per Woreda. *Source* Adapted from archives of regional and Woreda Water and Agriculture bureaus and present inventory

use/livestock watering. The provision of ponds for water storage could contribute substantially to agricultural development by saving time and energy in the collection of water, by reducing the incidence of water-related diseases (in terms of improving hygiene of the community) and by increasing livestock productivity. Unfortunately, many of these ponds are so poorly constructed that they fail to serve the purpose for which they were originally designed (see Sect. 3.3).

### 3.2 Socio-Economic, Environmental and Livelihood Impacts

The main purpose of constructing the dugout ponds was to conserve excess water available from floods or run-off to improve socio-economic condition and income of farmers. This can be achieved by shifting the rainfall-dependent agricultural practices into modern or supplementary irrigation systems. During field survey and random interviews and focused group discussions with elder farmers, the following qualitative results were obtained in relation to socio-economic, environmental and income or livelihood improvements around successful ponds: (1) increased farmers household income from that of rainfed agriculture (2–5 times income increment), (2) water availability for different uses increased, (3) availability of fodder increased, (4) diversity of birds species and beekeeping increased. Figure 7 illustrates various benefits of community achieved through water harvesting technologies in semi-arid areas of northern Ethiopia.

Different researchers obtained generally similar results as above from different parts of Ethiopia (Teshalle 2001; Woldearegay 2001; Behailu 2002; Pender and Berhanu 2002; Benin 2006; Nedaw and Walraevens 2009; Bantero et al. 2010; Bacha et al. 2011; Sisay et al. 2011) and from other different countries (e.g. Bhutta


**Fig. 7** Field photographs illustrating increase in income through irrigation (**a**, **c**), water availability and increase in fodder and local microclimate changed (**b**, **d**) through different water harvesting technologies in northern Ethiopia. *Photograph* Gebremedhin Berhane

1999; Murray-Kust et al. 1999; Saleh and Mondal 2001; Hussain et al. 2003; Hussain and Hanjra 2003, 2004; Munawar et al. 2004; Pavlov et al. 2006; Ashraf et al. 2007; Owusu et al. 2011; Wajid et al. 2013). The results of almost all these studies show that investment in agricultural water (like small water harvesting schemes, ponds, shallow hand dug well) is a positive and significant determinant of income and consumption, and a negative determinant of poverty (Hanjra et al. 2009). Few dugout ponds (with the exception of cement and plastic-lined types) in the area have limited unintended positive impact on groundwater by recharging shallow aquifers where farmers can abstract water by excavating big diameter shallow hand dug wells for various uses.

## *3.3 Technical Challenges*

Lack of proper subsurface data, experience on water harvesting, water use/management, information on attitude of the community, etc., have great contribution to the problems and failure of dugout ponds in Tigray.

The following points are the major challenges faced during the course of pond construction in the region (Table 1).

1. The depth of storage/pond is limited for manual construction, hence exposed to high evaporation.
2. Generally, construction is slow for hand dugout pond. Sometimes, it takes up to two years for such small structure.
3. Extracting large quantities of water from small dugout pond with motorized pump is not feasible. Water is drawn by rope and bucket or by walking inside the slippery surface of the pond which is time-consuming, unsafe and slow for irrigation.
4. Lack of soil survey and soil classification of the pond sites. This makes difficult to determine the side slope, to estimate volume of water lost by seepage and very difficult to get lesson from what was done.
5. Hard rock is very difficult to penetrate and often can only be accomplished by blasting, which is not feasible for such small structure (Fig. 8). Blasting damages larger area compared to the size of the pond under implementation in the area.
6. Difficult to penetrate deep enough into the sound or impermeable layers, so leakage/seepage from the storage makes unpredictable and makes non-feasible. Stored water on shallow fractured formation run dry within few days due to leakage/seepage.
7. Frequent failure of the side slopes/riprap stones and need for continuous maintenance (Fig. 9). The side slope was designed about 1:1.5–2.5 irrespective of material type change.

**Table 1** Summary of main challenges and their consequences related to dugout rainwater harvesting schemes in northern Ethiopia (Tigray)

| S. No. | Main challenges | Description and consequences |
|---|---|---|
| 1 | Limited depth of storage | Difficult to excavate greater depth, water exposed to evaporation |
| 2 | Slow construction | Takes up to two years for manual excavation |
| 3 | Slow water extraction | Walking inside pond is unsafe and time-consuming |
| 4 | Lack of soil survey and test | Difficult to design side slopes and estimate leakage loss |
| 5 | Hard rock difficult to penetrate manually | Blasting is not feasible for such a small scheme |
| 6 | Storing water in shallow and fractured medium | Unpredictable water loss via fractures |
| 7 | Failure of the side slopes/riprap stones | Need continuous maintenance |
| 8 | Lack of awareness in optimal water use and management | Stored water sometimes gets polluted without any use |
| 9 | Improper location or sitting | Results to lack of inflow and sedimentation |
| 10 | Lack of proper spillway construction and design | Excess water breaches the pond side and develop gullies |
| 11 | Improper decision on the type of pond | Plastic and cement-lined ponds increased cost of construction or initial investment |
| 12 | Poor handling of plastic liner | Plastics damaged during handling, recently most plastics from ponds were removed and used for different purposes (e.g. for shades in small towns, villages and big cities) |
| 13 | Improper construction of riprap | Plastics damaged by stone ripraps |
| 14 | Plastic liner is expensive for farmers | Cost of plastic sheet/liner is high and needs hard currency which is difficult for Ethiopian farmer |
| 15 | No fence and other preventive mechanisms incorporated in design | Potential for safety problem for animals and children. Many farmers complain with this situation |
| 16 | Lack of proper silt or sediment trap | Reduce storage capacity and life of the ponds |
| 17 | Site selection problem for ponds | Farmers select pond site from social or personal advantages perspective without considering or understanding technical suitability |
| 18 | Lack of standard design/guideline | No consideration of other water harvesting techniques during 2002–2010 |

8. Lack of awareness in optimal water use, management (Fig. 10), backyard irrigation and sanitation in the community.
9. Improper location or sitting of the dugout ponds with respect to surface inflow or run-off and sedimentation. The amount of rainfall and its distribution, run-off

**Fig. 8** Hard bedrock encounter at shallow depth. Location: Woreda Gulomekeda, Tabia Kileat. *Photograph* Gebremedhin Berhane

**Fig. 9** Improper side slope and frequent failure of riprap. Location: Woreda: Gulomekeda. *Photograph* Gebremedhin Berhane

characteristics, incidence of waterlogging and other relevant data were not determined.

10. Lack of proper spillway construction and design. A fully completed pond should be evenly sloped and grassed so that excess water will spread out and

**Fig. 10** Polluted dugout pond (stagnant water) could provoke malaria and poor construction finishing of side slope Location: Woreda Gulomekeda. *Photograph* Gebremedhin Berhane

**Fig. 11** Plastic liner damaged during transportation and storage. Location: Gulomekeda and Mekelle. *Photograph*: Gebremedhin Berhane

flow safely downhill into a natural drainage way, but this is not so in the study area.

11. Improper decision on the type of pond (clay, cement and plastic lining) in a particular site. Plastics were distributed on a quota bases to different Woreda/district rather than on the bases of soil survey and subsurface condition.
12. Considerable plastics (polyethylene liner) were damaged during transportation and construction processes (Fig. 11).
13. Improper construction of riprap directly on top of the plastic liner (missing soft soil cover on top of plastic) damages the plastic liner (Fig. 12). Damaged plastic liner is difficult to repair locally by framers, because the plastic is joined or patched by special equipment or heating sealing.
14. Plastic liner is expensive for farmers even though it is preferable for water storage in pervious formations and fractured and weathered rocks. The cost of

**Fig. 12** Sharp edged rock riprap damages the underlying plastic liner Location: Atsbi Womberta. *Photograph* Gebremedhin Berhane

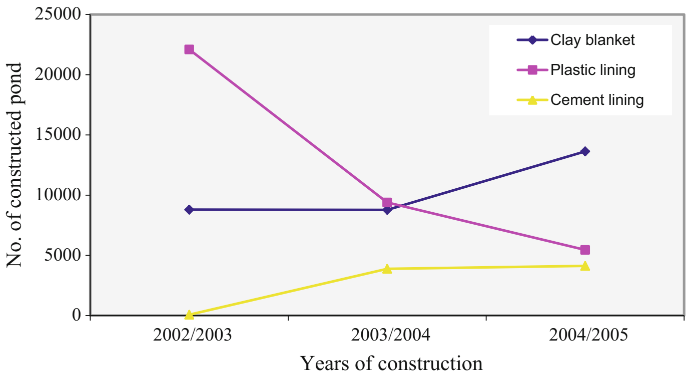


**Fig. 13** General distribution of pond-type construction during the years 2002–2005

plastic sheet/liner imported from Thailand or Indonesia is estimated 1575 ETB (nearly 80 USD) (Papavero 2004). Due to high price of the plastic liner and difficulty in transportation, construction of plastic-lined ponds was sharply reduced from above 20,000 in 2002 to about 5000 in 2005 (Fig. 13).

15. No fence and other preventive mechanisms were incorporated in the design of dugout ponds in the region. This situation is potential for safety problem for animals and children (Fig. 14). Moreover, rodents and insects may cause damage to some components of the pond.

**Fig. 14** Properly constructed dugout ponds [without fence (left) and with very simple wood fence (right)] from Gulomekeda and Atsbi Womberta Woredas, respectively. *Photograph* Gebremedhin Berhane

16. Lack of proper silt or sediment trap on the constructed ponds. This condition results in reduction of the storage capacity of ponds within a year. In places, about 40% of the normal volume loss due to sedimentation in some ponds located around a foot of hills.
17. The mistake made during the course of planning, design and implementation of dugout ponds was that most pond sites were selected by farmers or unskilled persons. Farmers or unskilled persons look/select pond site not only from technical point of view but also from social or personal advantages perspective. This procedure leads to improper sitting of many dugout ponds with respect to topography, catchment hydrology/size, proximity to household, vegetation coverage, water tightness, etc.
18. Lack of standard design, for example, where topographic conditions favour, especially in embankment ponds, no proper inlet/outlet structure was incorporated in the design. This creates a problem in water use and management.

The highlighted challenges mentioned above are linked with low capacity building and/or related to lack of awareness of the community and decision-makers. Planning, study, design, implementation and management of water harvesting schemes at different levels in the region are also less effective and weak due to lack of experiences and sufficient skilled manpower in the sector. Some improvements were observed during the subsequent years, probably after many failures of the dugout ponds because of experience and lessons obtained from the failures. At this point, the special solution to improve or minimize the challenges or failures in many water harvesting/storage projects is an integrated capacity building from the grass-roots farmer up to the higher decision-makers in the region to have a common understanding regarding the importance of these technologies and their challenges at all levels. Capacity building should be directed not only on the technical aspect of the water sector but also on water and poverty, governance, food and environment, water education, agricultural water management and financing water infrastructures to improve water use efficiency, productivity and sustainability. It is urgent to create a platform of better communication and common understanding among all those who are involved in the water resources affairs as the impact of climate change on water resources is becoming important in Ethiopia and many other arid and semi-arid regions of the world (Biazin et al. 2012; Abdi et al. 2013; Hadgu et al. 2013; Abrha and Simhadri 2015; Mikova 2015).

## 4 Discussion

The economy of Tigray mainly depends on agriculture, and this in turn largely depends on available water resources (Biazin et al. 2012; Grum et al. 2016). Farmers in rural Tigray live in a shock-prone environment attributed to continuous rainfall fluctuations (Hadgu et al. 2013; Abrha and Simhadri 2015). The major objective of the dugout water harvesting pond is to provide supplementary irrigation and domestic/livestock uses. Hence, their contribution towards alleviating the poverty and food insecurity problems is important, provided proper utilization system is in place. Initially, one pond was planned to irrigate about 200–500 $m^2$ land. The inventory (conducted in 2008) shows a maximum of 50 $m^2$, but many of the ponds do not irrigate at all due to various problems mentioned above. There are better opportunities for vegetables depending on market availability. According to Mills (2004), ponds in Tigray can contribute significantly to household incomes and enable farmers to purchase between 30 and 80% of their food needs by selling vegetables irrigated/planted with water from ponds. A study conducted in Atsbi Womberta Woreda (one of the 31 districts in Tigray) by Papavero (2004) reported that most of the irrigation systems are surfaced or gravity systems, whose efficiency is normally between 60 and 70%. This means that 60–70% of the water applied to the field is used for evapotranspiration by the crop, while 30–40% is lost by surface run-off from the lower end of the field and by deep percolation of water that moves through the root zone (Papavero 2004). To increase the benefits out of dugout pond, more efficient water application systems manageable by farmers are important to improve productivity by increasing size of irrigated land. In fact, an on-farm experiment regarding water harvesting, lifting system, evaporation, seepage, irrigation system is crucial for deep insights and understanding of local situations.

If the various problems in dugout pond construction in particular and water harvesting programs in general remain unresolved, the social and environmental consequences and their associated costs will be significantly high. In general, when a project is planned and implemented, a multidisciplinary approach must be followed if a project is to be completed for optimum benefits and minimum adverse effects. Emerging problems directly undermine the sustainability of key technical, social and environmental services society depends upon (Louis and Garland 1996).

What the future may hold depends heavily on whether or not processes capable of generating mutual understanding of management needs. Capacity building, strong institutional set-up in the sector and mechanisms of implementation and quality control are also key factors. To maximize the benefits from dugout pond or other water harvesting projects, it has to be planned or designed as a multipurpose project (water supply, irrigation, fire protection, livestock watering, flood and erosion control, fish and wildlife production or recreation, etc.). In other words, the purpose should be clearly defined and design and construction be done accordingly.

Out of the challenges and problems faced in construction of dugout ponds, excessive water loss by seepage is ranked number one (Boyd 1982). In about 60% of the inventoried ponds, seepage problem was observed. Excessive water losses by seepage in ponds usually are due to the selection of a site where the soils are too permeable to hold water or underlain by fractured bedrock (Boyd 1987). Selecting a suitable site for a pond site is important, and preliminary studies are needed before final design and construction (USDA 1997). With respect to the dugout ponds in the study area, it is the result of inadequate site selection and investigation in the planning stage. The lining of clay, plastic and cement looks better in terms of leakage prevention in northern Ethiopia, but it needs further detail for performance evaluation.

The problem of reducing seepage losses is one of reducing the permeability of the soils to a point where the losses become tolerable. Integrated and different mitigation methods should be introduced in the region. Out of which sealing by compaction alone, clay blankets, sealing with bentonite, treatment with chemical additives and use of flexible membranes are favourable (Boyd 1982). Even though water loss by seepage is reduced by the aforementioned methods, the choice of which methods to apply depends largely on the proportions of soil materials (texture) to be sealed or blanketed (Boyd 1982). Hence, a thorough investigation of the materials at the pond site should be made by a soil expert or geoscientist. In complicated site condition in terms of variability in soil type and geology, a laboratory analysis of the materials is necessary. As mentioned above, sealing the pond by clay blanket and plastic liner was already exercised in the study area (Fig. 15). These effective activities are changing positively the lifestyle of the rural population in some areas.

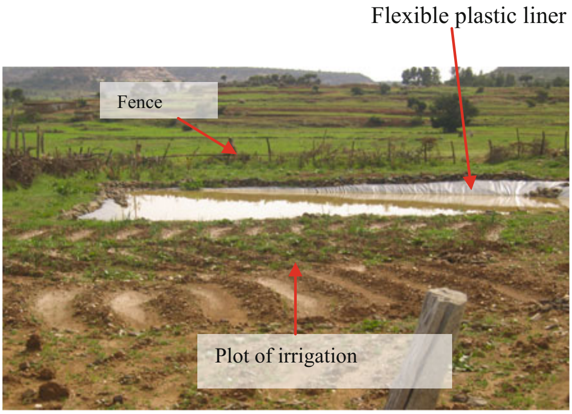


**Fig. 15** Plastic-lined pond with fence and micro-irrigation nearby the pond from Atsbi Womberta Woreda. *Photograph* Gebremedhin Berhane

## 5 Conclusions

It has been observed that almost all the areas in the arid and semi-arid regions of the study area experience moisture deficit and irrigation shall supplement the rainfed agriculture. Nearly 50–60% of the dugout ponds in the study area are not supplementing the rainfed agricultural crop due to technical problems faced during design and construction, lack of proper water conveyance mechanism, poor understanding of the community and extension agents/local administrators in supplementary irrigation, improper site selection and poor understanding of the role of subsurface materials on seepage/leakage losses.

Depending on the variability of rainfall, demand for different uses and suitability of topography and geological conditions, different types of pond and water harvesting schemes should be introduced in the region to minimize water scarcity and upgrade irrigation and water supply coverage. In deciding type of water harvesting, its size, design and seepage preventive measures criteria like problems in obtaining water (extent of water scarcity), frequency, degree and duration of water shortages and other design parameters should be considered into account. Site selection for dugout pond should be conducted by a technician with reasonable knowledge of soil and geology of the area or by an engineering geologist. A wide range of capacity building (development) for all actors in the water sector in the region is very important to make water harvesting programs successful. In addition, it is relevant to systematically investigate the causes for low adoption and disadoption rates since without water harvesting farmers may be more prone to water shortage, leading to lower and more variable agricultural production and vulnerable to drought. Quantitative survey on the impact of dugout ponds on groundwater recharge is recommended.

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# Innovative Rainwater Harvesting Technologies for Pastoralists in Arid and Semi-arid Areas: A Case Study in Oromiya Region, Ethiopia

**Alemayehu Haddis**

**Abstract** This paper introduces innovative rainwater harvesting technologies that are designed to solve problems of evaporation, percolation, contamination, and vector-borne disease propagation. The paper also tries to adapt a pilot-tested technology from high rainfed geographical locations to arid and semi-arid ecosystems and while doing this local sociocultural, economic, and environmental factors play key role to success. This study contributes to the development of efficient ways to manage and use rainwater in water-scarce arid and semi-arid areas in Ethiopia for domestic and livestock purposes and for income diversification.

**Keywords** Incubation · Income diversification · Evaporation · Water quality
Water quantity

## 1 Introduction

### *1.1 Background*

Access to water is a fundamental human rights issue and is central to sustainable development. However, for the world's poorest citizens, the right to safe water supply and adequate sanitation remains a promise unfulfilled (UNESCO-IHP 2006).

To the pastoralist communities in Borena Zone, rainwater remains the only reliable source as surface water is quickly lost by evaporation and groundwater is too expensive to access. On top of this, rainfall is highly unpredictable. Arid areas usually experience short rainy seasons followed by longer dry periods. In some cases, rainfall could be intensive and runoff in the dry ephemeral stream beds flows in the form of rivers. But since this flow is in response to the direct rainfall event, it

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emerges in the form of flood which dries and leaves the river beds with silt deposits in few weeks after rainfall.

Tapping rainwater is not simple in arid regions. It follows a much more complicated pattern which is usually difficult to manage. For example, in Namibia, an arid region with 250 mm mean annual rainfall, it is estimated that only 2% of the rainfall is available as runoff and about 1% of the precipitation recharges groundwater. About 83% of the rainfall evaporates shortly after rainfall. The rest 14% infiltrates into the soil to be used up by natural vegetation (Heyns 2009).

Hence, in rainwater harvesting, practitioners are competing for the very small fraction of water that flows as runoff and stays only for a short period of time. The definition of rainwater harvesting by Mekdashci and Liniger (2013) reflects this condition and is stated as "*the collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural uses as well as ecosystem sustenance*." Rainwater has been in use since early Roman civilizations and ancient Egypt that dates back at least 2000 years or even 4000–5000 years in India (UN HABITAT 2005).

Although the use of rainwater to boost domestic water supply and sanitation programs is highly applicable in areas of high rainfall intensity, arid and semi-arid areas also have no choice, especially in situations where there is increasing water stress (Heyns 2009; ACCES 2011). So far it has not been possible to solve the problem of water in pastoralist communities in Borena Zone. The effort of communities, NGOs, and the government in addressing water problems by intensifying rainwater harvesting programs has not been effective. Most of the water has dissipated quickly by evaporation, the quality is not good for domestic purposes and other unanticipated outcomes like the propagation of mosquitoes intensify (Boelee et al. 2012). This has resulted in frustration among communities.

The major question in this project is how best to design and introduce rainwater harvesting program in a way that can sustain life, i.e., provision of clean and adequate water supply without adverse health and environmental impact and used in income diversification and climate change mitigation for communities in Borana Zone, SW Ethiopia.

## 1.2 History, Role in Development and Challenges of Rainwater Harvesting in Ethiopia

The history of water harvesting in Ethiopia dated back approximately to 560 BC. Anthropological evidences of pond remains of this era and the roof catchment remains still visible in one of the oldest palaces of the Axumite Empire are suggestive of the use of RWH during the ancient Ethiopian civilization (Getachew 1999). The water harvesting setup at Fasil castle in Gondar, which was Ethiopian capital during the fifteenth to sixteenth century and the long-standing and well-established practices among the Konso people in SNNPRS prove that water harvesting practices in Ethiopia have been well established (Getachew 1999).

The idea of water conservation which was then termed as soil and water conservation started in late 1960s in Ethiopia without distinction between water harvesting and rainwater harvesting. Both of these terms were indiscriminately being used and limited to the construction of micro-ponds, ponds, and dams for collecting rain event runoff (Yohannes 2014). The 1974 drought was followed by the construction of dams such as the Fedis areas of Eastern Ethiopia and earthen dams and ponds in Tigray and Wollo of northern Ethiopia. Following the 1984 drought, the military government again repeated the previous experience of building dams and ponds in a campaign mode but this time more linked to small-scale irrigation than domestic water supply. The post-1991 era of the current ruling party, EPRDF saw a dramatic boom of dams and ponds in the country. The major problem of this phase is that it started from scratch without trying to learn from the success or failure of the past experience. This era as elaborated by Yohannes (2014) can be looked to have two distinct phases namely:

1. The micro-dam sub-phase that started in the second half of the 1990s with the establishment of the "Sustainable Agriculture and Environmental Rehabilitation Program (SEARP)" mainly in the northern regions of Ethiopia. This was a multi-million Birr project aiming to construct hundreds of micro-dams and later on incorporating earthen dams and ponds. Experience from micro-dams in Tigray revealed quick evaporation and seepage before the project is intensified to other regions. New disease like Schistosomiasis and malaria also became a threat.
2. The ponds sub-phase which became an area of focus during another cycle of drought in 2003. The focus now was ponds, not dams. During this phase, every farmer was encouraged to have his own pond for rainwater collection.

The recurrent drought in Ethiopia has forced the policy makers to advocate for collection of rainwater by digging ponds on farm plots. The government has established commissions (commission for sustainable agriculture and environmental rehabilitation (COSAER)) in four regions: Tigray, Amhara, Oromia, and Southern Nations. The mandate of the commission was to promote, develop, and manage regional land and water resources, rainwater harvesting being the major task (Getachew 1999). This method, which is practiced nationwide, has had significant contribution for agricultural productivity and in sanitation promotion. The practice, however, has resulted in adverse health effects. New diseases that were not reported before started to spread among inhabitants around the pond. According to Mintesenot and Haile (2003), some negative impacts are being observed, especially on soil salinity and erosion. Malaria has become a growing concern in micro-dam areas with altitude lower than 2000 meters above sea level (masl). It was also reported that "these days, the use and promotion of ponds even for livestock watering are increasingly becoming difficult and challenging due to the spread of deadly childhood malaria, and for this reason, most NGOs are unable to promote and support pond construction due to environmental constraints" (Getachew 1999).

The disappointment from the failure of the mass pond program in Ethiopia created an atmosphere of despondency and silent withdrawal at all levels of the government. Since then, there is no more national level program in RWH. This was left to lower administrative levels, and NGOs to go their own way (Yohannes 2014).

## 1.3 Water and Poverty Linkages

Human development and survival cannot be assumed in the absence of water. According to the MDGs target of the UN, it was planned to eradicate extreme poverty through education and ensuring environmental sustainability, in which access to water was one of the areas of emphasis. But this seems to be unachievable before 2030 (Munir et al. 2009; UNEP/SEI 2009). Generally, there is water stress in many parts of the world which is a major contributing factor for poverty. According to the UNEP report, Asia and SSA are the regions worst affected by food insecurity and malnutrition, and yet, they are home to 60% of the worlds food insecure people and 75% of its children are malnourished (UNEP/SEI 2009).

Ethiopia has been considered as the water tower of Africa. However, the country is projected to be under economic water scarcity in few years to come (Rijsberman 2006). It is further projected that Africa will face increasing water stress. As 50% of Africa's rivers are trans-boundary, subsequent water conflicts in the region are expected. The scarcity of water that is being observed and becomes worse from time to time will severely compromise productivity of the rainfed agriculture. This would open doors for poverty traps. The poverty traps stem mainly from limited access to productive assets such as land and water, high dependence on agriculture, low farm productivity, low levels of human capital, poor infrastructure, and underdeveloped market systems (UNFCCC 2007; Munir et al. 2009).

## 1.4 Causes of Vulnerability to Climate Change and Water Stress in Ethiopia

Water stress has been implicated to climate variability. Africa is already a continent under pressure from climate stress and is highly vulnerable to the impacts of climate change. The climate in Africa is among one of the most variable and unpredictable phenomena exhibited by extreme events of drought and famine on one side and floods on the other that occur more frequently and suddenly (USAID 2011; Misra 2014).

Many factors contribute and compound the impacts of current climate variability in Africa and will have negative effects on the continent's ability to cope with climate change. These include poverty, illiteracy, and lack of skills, weak institutions, limited infrastructure, lack of technology and information, low levels of primary education, and health care, poor access to resources, low management capabilities, and armed conflicts. The overexploitation of land resources including forests increases in population, desertification and land degradation pose additional threats (UNFCCC 2007; Misra 2014). Moreover, climate change and global warming will intensify the prevalence of tropical vector-borne diseases like malaria.

In climatological terms, a large part of the Ethiopia is defined by dry sub-humid, semi-arid, and arid, which is prone to desertification and drought. The Ethiopian highlands constitute a fragile ecosystem that are stressed by population pressures and related socioeconomic activities. Historically, the country has faced major natural and manmade hazards that imparted significant pressure on productivity, health, and survival of the population.

Drought and famine, flood, malaria, land degradation, livestock disease, insect pests, and earthquakes have been the main sources of risk and vulnerability in most parts of the country (MoWR 2007). Climate could be the cause for most disasters but unregulated or uncontrolled human activity especially when coupled with poverty can have significant contribution to environmental degradation that in turn can lead to climate change.

## 1.5 The Role of RWH as a Coping Mechanism to Extreme Events

There are a number of traditional coping mechanisms to climate variability and extreme events in Ethiopia. However, for better and sustainable adaptability, these traditional mechanisms need to be reenforced by knowledge and should be based on scientific approaches. Some possible coping mechanisms in these areas could be linked to new approaches and technologies in cropping and planting practices, adjustment and wastage minimization to food consumption habits, improve the consumption of wild fruits if proven healthy, inter-household transfers and loans, increased petty commodity production, animal fattening (using failed crop to feed animals), switching between agriculture and other employments as needed, credits and food aid appeals and use of early warning systems (USAID 2011).

For all these strategies to work, water plays a critical role. Water is scarce in areas where the pastoralists live in Ethiopia. The only possible means is to catch and store every drop of rainfall. Precipitation is available and good every year; however, the problem is that it is variable and unpredictable. For this reason, every farmer needs to be alert and get ready to collect and store rainwater for use during the driest seasons.

### 1.6 Challenges with Existing Water Catchment Technologies

Observations from a one-year field experience to the region revealed that the open ponds and reservoirs have become good breeding places for malaria mosquitoes. The reservoir gets dry in few days because of intensive *evaporation* and *percolation*. The water in the reservoirs which is usually consumed for drinking and domestic purposes is *highly turbid* and *contaminated*. Another major problem observed was that areas that were free of malaria manifest themselves in outbreaks of malaria, a burden which cannot be tolerated by the community which already has a compromised resistance to diseases because of hunger. This was supported by a report by Mekonnen and Mitiku (2010) showing that 268 of the 990 blood sample from children <10 residing nearby half-moon ponds were positive for malaria.

These field observations triggered the idea of development of an innovative rainwater harvesting technologies that are able to prevent quick water loss, improve quality, and prevent multiplication of mosquitoes. To this effect, different version of RWH technologies was developed and field tested and evaluated in Jimma area, southwest Ethiopia.

### 1.7 Objectives

The overall objective of the project was to develop and test an innovative local technology for rainwater harvesting in Jimma area for possible future use to more needy pastoral communities of Borena Zone in Ethiopia. The tested technology needs to prove that it improves access to water supply which is low cost, safe, long-lasting, and sustainable.

## 2 Methodology

### 2.1 Study Area

A pilot rainwater harvesting system from surface catchments was developed and tested for its efficiency in Serbo, Kersa woreda, Jimma area in 2006. Specific design features like rainfall, settlement pattern, and environmental conditions will be considered when the technology is transferred to Borena.

## 2.2 Methods

Four basic principles of design were introduced.

1. Catchment collection coefficient was assumed to be 0.7.
2. The media used needs to assist in water purification/filtration.
3. Evaporation should significantly be minimized.
4. The system should be mosquito proofed.

The design also considered the following input parameters.

- From the zonal meteorology office, it was found out that the average annual rainfall of the area ranged between 1700 and 2000 mm.
- As collection was done during the main rainy season, the highest rainfall event (2000 mm) was considered for this specific project
- The dry season of the area was 4 months
- Per capita consumption = 10 L/c $d^{-1}$ (only for domestic purposes).
- Family size = 4

This data was used to determine the collection surfaces with variable runoff coefficient. Figure 1 shows a prototype of the design.

Three variations were constructed and tested for better performance for set indicators:

1. Design 1 site 1: Water collection surface with plastic sheets and the reservoir bed with concrete and thatched shading over the pond. This design is designated as PCT.
2. Design 2 site 2: Water catchment surface with grass and the reservoir bed with plastic sheets (half of the retention wall with masonry) and thatched shading over the pond (designated as GCT).
3. Design 3 sites 3 (at Serbo Health Center)—both collection surface and collection reservoir with concrete and thatched shading over the pond (designated as CCT).

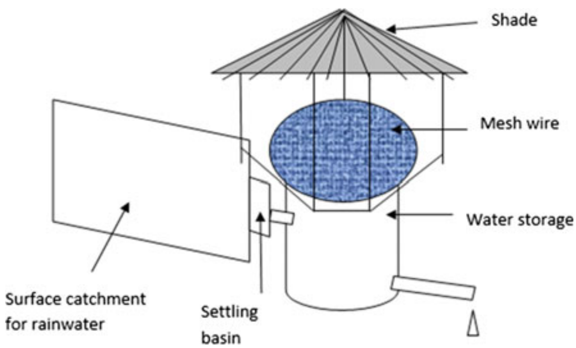


**Fig. 1** Schematic representation of the pilot and innovative rainwater harvesting technology

4. A control with no plastic sheet, concrete, or grass as a catchment surface and no shading (designated simply as *C*).

During design and construction, special attention was given to maintain the four design principles mentioned above, as it is shown below:

- Mesh wire was applied on top of the pond to prevent contact of mosquitoes with the collected water. An oval domed-like shape was created on top of the reservoir by using iron bars to support the mesh. Outcome indicator will be number of mosquito larva or adults found on the water sample.
- Water loss due to evaporation was prevented by applying thatched roof over the pond, but the water still gets aerated below the shade. Outcome indicators will be number of months served by the available water.
- Water loss due to percolation was minimized by applying either plastic sheets or concrete in the collection reservoir. Outcome indicator is same as above.
- The surface catchment was improved either by layering with plastic sheet or by concrete floor with settling basin so that better quality water is secured. Outcome indicators will be turbidity, TDS, and coliform count. The pilot project sites were selected after community consultation using the following criteria.

### 2.3 Site Selection and Community Consultation for the Pilot Project

For the pilot project in Jimma, final-year environmental health students were attached to the project and were engaged to the whole process (Fig. 2) from designing, site selection, community consultation construction, and evaluation.

The following criteria were used to select the site:

1. The plot owner is willing to devote his land.
2. The plot owner will participate in the construction and avail local materials.
3. The community shows willingness to assist the plot owner, learn from it, and construct their own RWH system.
4. The site to be selected has gentle slope and demands minimal labor to get the desired slope.
5. The soil is intact and not cultivated before.
6. The site is away from heavy flood line and other contamination risks from human and animal excreta, pesticides, and other chemicals.
7. The site has sufficient space for surface collection and storage.

**Fig. 2** Jimma University environmental health students at site selection mission. *Photograph* Alemayehu Haddis

## 2.4 Community Consultation

The Health Center at Serbo town then organized a consultative meeting with farmers around the plot and the Kebele leaders (Fig. 3).

## 2.5 Construction

Construction was participatory. Involved stakeholders were the plot owner, community leaders, Serbo Health Center, and Jimma University staff and students. Figures 4 and 5 are snapshots from the construction.

Once proved to work, literature survey on Borena Zone, in general, and Arero district, in particular, will be conducted to learn about rainfall patterns, local water harvesting practices livelihood practices, and environmental factors like soil type and vegetation cover. The tested and selected rainwater harvesting system in Jimma will then be adapted, and specific design parameters will be used in incubating the technology in Borana Zone. The following steps are followed in incubating the new tested technology in Arero district–Borena Zone.

**Fig. 3** Farmers and Kebele leaders' discussion the project. *Photograph* Alemayehu Haddis

**Fig. 4** Construction of grass collection catchment (GCT). *Photograph* Alemayehu Haddis

**Fig. 5** Half-concrete and half-plastic lined water collection reservoir. Note the mesh wire supporting bars being installed on top of the water reservoir. *Photograph* Alemayehu Haddis

# 3 Results

## *3.1 Pilot Project*

A one-month rainfall in August was sufficient enough to fill the reservoirs from the surface catchment. Reservoirs were kept for the month of September during which mosquitoes proliferate. Evaluation was done from October to January 2006. Based on the evaluation of the three designs, the following results were obtained (Table 1).

The runoff coefficient Cr is a dimensionless empirical coefficient which is estimated from the combined effects of infiltration, depression storage, evapotranspiration, and interception (USGS 2006). The runoff coefficient ranges between 0 and 1.0. A basin that has low land-surface slopes, high infiltration rates, high groundwater storage, and extensive vegetation, and surface storage will have a low runoff coefficient. A steep basin with an impervious surface, little vegetation, and no surface storage will have a high runoff coefficient (USGS 2006). In this experiment, the grass filter (GCT) has the smallest runoff coefficient which is 0.25.

The catchment surface area was smaller for concrete collection surface because it was assumed that there will be high runoff coefficient. Although size reduction was an advantage, turbidity was higher on the other hand. This could be due to surface wearing and washout of cement and or sand as the water flows on top of it.

**Table 1** Comparison of selected evaluation parameters for the three designs and the control of the pilot study in Serbo, Jimma area

| Parameter | PCT | GCT | CCT | *C* |
|---|---|---|---|---|
| Runoff coefficient | 0.35 | 0.25 | 0.75 | 0.15 |
| Catchment surface area ($m^2$) | 72 | 100 | 35 | 120 |
| Storage tank capacity ($m^3$) | 5 | 5 | 5 | 5 |
| Service length for one family (days) | 97 | 108 | 110 | 46 |
| Mosquito larval count | – | 2 | – | >20 |
| Adult mosquitoes trapped | – | – | – | 5 |
| Turbidity (NTU) | 13 | 12 | 16 | 65 |
| TDS (mg/L) | 1800 | 1500 | 2000 | >3000 |
| Coliform count per 100 ml of sample | 10 | 7 | 8 | 50 |

*PCT* Plastic catchment surface, collection reservoir made of concrete and thatched shade; *GCT* grass catchment surface, collection reservoir made of concrete and thatched shade; *CCT* concrete catchment surface, collection reservoir made of concrete and thatched shade; *C* control with natural ground surface, reservoir without concrete and no shade

The low runoff coefficient of plastic surfaces could be due to poor material selection. This could have been significantly improved if HDPE is used. The design period is slightly lower than originally planned. This could be due to lower wastage assumptions (only 5%). Even then the service period of the three experimental designs was more than doubled when compared to the control. This suggests evaporation and percolation to be minimal in the newly introduced designs. There is significant improvement of turbidity by the intervened catchments than in the control although they still exceed WHO standards for drinking water which is set at 5 NTU (Tebbutt 1983). TDS slightly exceeds WHO guideline values which is 1000 mg/L (WHO 2003). Total coliform count for the intervened surfaces is significantly lower than the control because of the diversion ditch in the former systems which prevent contamination from open defecation.

## *3.2 Adaptation and Incubation of a Tested Technology from Wet to Arid Regions—Jimma to Borena*

### 3.2.1 Overview of Pastoralist Communities in Borena Zone, Oromiya Regional State, Ethiopia

The pastoralists in Ethiopia constituting 12–15 million are mainly found in lowland regions of Afar, Oromiya, Somali, and Southern Nations, nationalities and people regional state (SNNP). Pastoralist groups are also found in Gambella and Benishangul regional states (Sara and Mike 2008).

Borena is a pastoral zone located in the southern part of Ethiopia bordering Somali region in the east, northern Kenya to the south, Guji Zone to the northeast, and SNNPR in the west (Fig. 6). It is one of the 18 zones in Oromia regional state located in the arid and semi-arid southern lowlands. Livestock is the vital source of food and income in a population of about 1 million residing in the zone.

In the absence of catastrophes, the zone is one of the major sources of livestock supply in the local and international markets. During the last consecutive years, Borena has been repeatedly experiencing complex humanitarian crisis as a result of drought, conflict, and disease. Massive livestock death due to drought in the last decades, particularly in the last five years, has badly affected the livelihoods of the communities and the overall food security in the area. The bimodal rainfall regime is prominent in Borena rangelands in most of the districts. Annual average rainfall ranges from 400 mm in the south to 600 mm in the north. Fifty-nine percentage the rainfall occurs during March to May and 27% in September to November. The major rainy season (March–May) locally known as *Ganna* and the short rains from October–November called *Hagaya* are the two rainy seasons. *Adollasa season* is characterized by dry and cool temperature which occurs between the main rains and short rainy season (Inter agency rapid needs assessment 2011).

Water sources in Borena Zone are scarce. Surface water is available only during rainy seasons. Groundwater table is too low making the development of deep wells

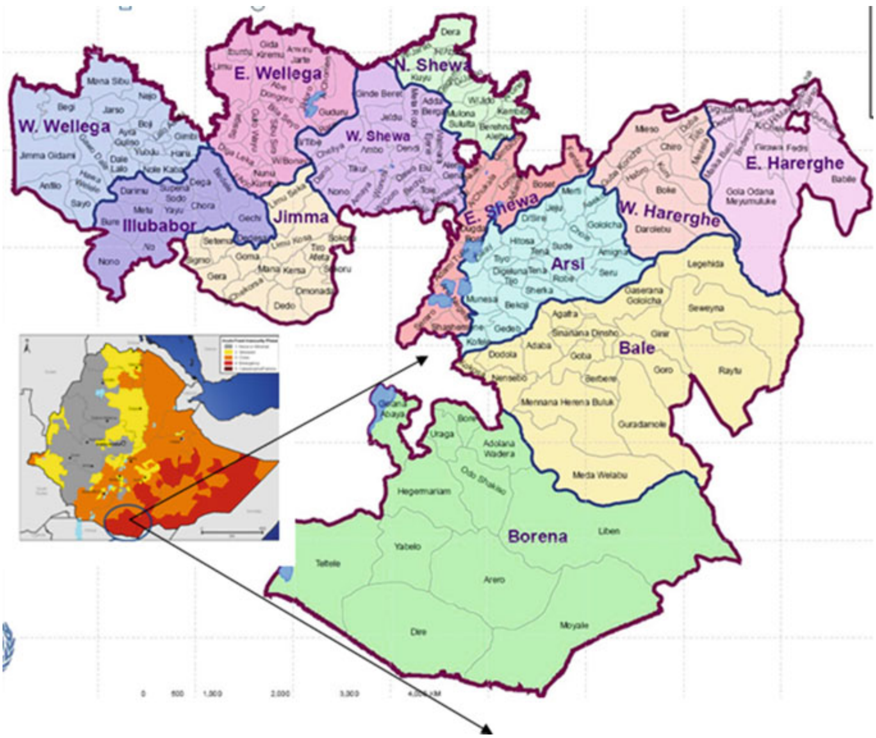


**Fig. 6** Location of Borena Zone in Oromia region, southern Ethiopia

extremely expensive. Hence, options are needed to improve access to water sources and rainwater harvesting is a promising one. There is already a local knowledge of using rainwater in this area. What is needed is to upgrade and build upon existing knowledge.

The current practice of rainwater harvesting cisterns in Borena and other pastoralist communities in Somali and Afar regions are not safe to drink and last only few weeks. Although Ethiopia's Borena Zone has some of the most elaborate water control and management system (Nassef and Belayhun 2012), because of the high concentration of pastoralist communities around water sources, there is an over-exploitation of both water and grazing land and as a result, environmental damage is high.

Rainwater harvesting is an option and in some places of arid and semi-arid landscapes (ASAL) the only option as a source of water. A lot of investments have been going on RWH as farm ponds in Ethiopia to solve the problem of water scarcity and improve livelihood. However, availing water is not the only solution. A lot of dimensions have to be assessed: health, climate, cost, amenity and acceptability of the technology, local socioeconomic, and environmental dimensions. An innovative RWH design approach is needed that address issues of quality, quantity, health, and resilience to climate change using local knowledge and material to develop a low cost but efficient technology in rainwater harvesting. By introducing such a low cost and efficient technology that is able to collect and provide sufficient and good quality water, previous disappointments of the pastoralist communities will be substituted by willingness to absorb and sustain the technology. As rainwater is the only option in some areas of this community, innovations will lead to improve resilience and intensify diversified livelihood.

Observation of the existing traditional rainwater collection cisterns reveals that the water is highly turbid and prone to fecal contamination. The water ponds are also exposed to mosquito breeding thereby increasing the risk of malaria among the pastoralist community. The other problem is the water cannot be contained for an extended period of time because of the rapid evaporation and percolation. This project, therefore, aims at introducing innovative rainwater harvesting technology from surface runoff in Borena Zone that is economical, safe, and long lasting.

### 3.2.2 Design of the New Innovation Suggested for Incubation in the Pastoralist Communities of Borena Zone

It is critically important that rainwater harvesting technologies that are introduced in pastoralist communities in areas like Borena Zone need to be significantly improved from the traditional ones, be of low cost and sustainable. First, physical data and material inventory should be conducted. The intensity of rainfall and the dry season period shall be used in the design as described by the following relationship.

$$S = R \times A \times \mathrm{Cr}$$

$S$ Mean rainwater supply in $m^3$ (Storage tank capacity)
$R$ Mean annual rainfall in mm/year
$A$ Surface area of catchment in $m^2$
Cr Runoff coefficient

The design period will be 3–4 months, and the tanks will be filled twice a year as there are two rainy seasons (September to October and March to May).

Based on available physical data and local materials, a system with surface collection surface can be constructed. First an appropriate plot of land with wider and gentle field in the middle with a slope between 1.5 and 2% will be needed. It is a quality advantage to intercept the surface flow by larger gravel with 100 mm Θ on both sides to slow down the flow and trap larger objects. The wider surface will then be preserved/planted with grass on a calculated catchment. The grass cultivated from the catchment surface will be used as animal feed. The down end of the grass collection surface will be channeled through a subsurface sand bed to serve as a filter. The effluent from this sand filter will be led to a two-compartment watertight tanker made of concrete or lined with HDPE depending on cost factors.

**Design data**:
Consider:

- Average family size to be 5 persons.
- Water consumption per capita per day is assumed as 30 L (20 L for domestic use and 10 L for weak animals and calf).
- Dry period = 4 months for short rainy season and 3 months for long rainy seasons (4 months is considered to be on the safe side).
- Settlement pattern of the community is clan based (at least 10 households and the water needs to be shared).

1. Collection reservoir capacity will then be:
   50 persons *30 L/d * 120 days = 180,000 L or 180 $m^3$.
2. Required collection surface area.
   From the relationship given above:
   $A = S/(R \times \mathrm{Cr.})$
   $S = 180\ m^3$
   $R = 358$ mm (0.358 $m^2$). This is assuming that the total rainfall during the two rainy seasons is 716 mm as obtained from local data and that precipitation in dry seasons is negligible.
   As the system is lined and shadowed, percolation and evaporation are also negligible.
   Take the coefficient of runoff (Cr) for grass filters as 0.4.
   Hence: $A = 180/(0.358 \times 0.4) = 1257\ m^2$ or nearly 0.13 ha.
   Dimensions can be estimated based on local topographic conditions.

As can be seen from the sketch in Fig. 7, the reservoir is divided into two compartments. The first compartment will be used as settling tank and the second and larger compartment as clear water reservoir. The clear water reservoir fitted with a faucet will exclusively be used for domestic purposes, and drainage point from the first compartment will be used for cattle and irrigation. The open concrete water tank will be screened with mesh wire using stick support, and local materials will be used to construct a two-meter high shade (grass and logs). Two such systems will be constructed in two different kebeles and will be compared for quality and quantity with existing facilities.

The four principles of design mentioned under 4.2 were in this case upgraded to 5 including costs as a fifth principle.

Water loss due to evaporation can be prevented by constructing a shade using local materials like wood, grass, or crop residues. The free air movement beneath the shade helps to cool and ventilate the collected water. The top open surface of the water can be screened with mesh wire supported by bow-shaped logs or bars. This helps to prevent mosquito breeding on or near the surface of the water.

The collected water will be monitored for quality and safety. Larval survey will be conducted at the same time. Finally, cost–benefit analysis will be conducted and sustainability measures will follow. The sustainability measures include training of water and sanitation workers, beneficiaries, and other stakeholders operating in the region. The local governmental and other traditional leaders will be sensitized to create enabling conditions to introduce and scale up the technology to other parts in the zone. The whole catchment (from the stone trap to the distribution point) will be fenced to avoid disturbance and damage to the structure. Environmental restoration and conservation activities along the collection catchment will be done by planting

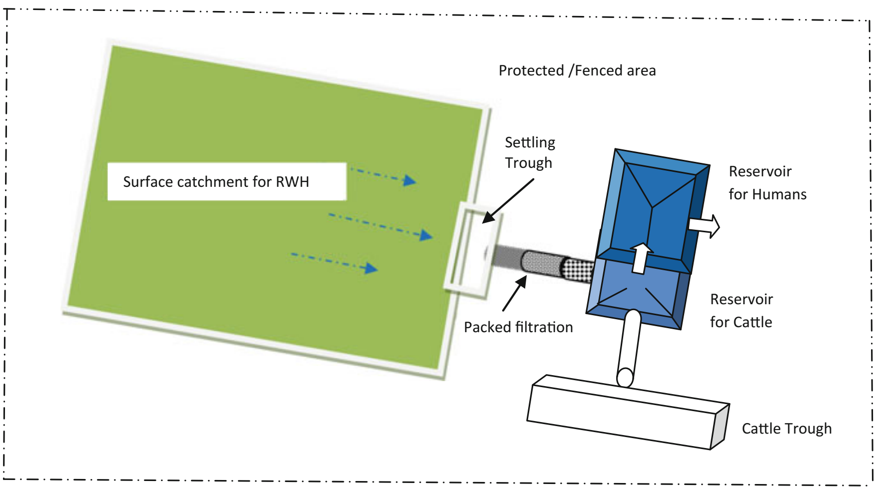


**Fig. 7** Sketch of the site plan for the proposed rainwater harvesting catchment in Borena

drought-resistant tree species like cactus and Moringa which are also good in purifying water. This activity also helps to create resilience to climate change.

### 3.2.3 What Is Innovative About This Project?

- First and foremost, the project introduces *integrated* approach in RWH aiming at climate resilience, diversification of livelihoods, and protection of public health.
- The project introduces a pilot-tested design to pastoralist communities in Borena Zone with mechanisms that can tackle the problem of percolation and evaporation—an advantage that will *prevent rapid water loss*.
- It uses local filter material like grass stones and gravel to improve the quality of rainwater, hence *minimizing cost* but at the same time giving the best *quality* of water.
- It is designed to avoid multiplication of mosquitoes that transmit *malaria* disease.
- It follows an integrated approach which can lead to diversified livelihoods and climate resilience.
- It depends on rainwater that is the only reliable source in areas where groundwater table is low and surface water does not exist.

### 3.2.4 How the Innovation Will Contribute to Resilience-Building in the Region

This innovation follows an integrated approach for water and food security, diversification of livelihoods, climate mitigation, and resilience building. Figure 8 illustrates how this particular innovation is linked to resilience building.

As a further step to climate change mitigation and environmental rehabilitation, the area around the catchment will be planted with fruits and drought-resistant trees. This action will also assist to improve the water quality before it enters to the collection catchment. Such an approach will make the project integrated in climate change mitigation, diversification of livelihoods, environmental rehabilitation, and improved access to sanitation. In this case, the community will have a chance to have a more resilient building capacity when faced with adverse impacts of climate change and drought. Integrated RWH practice such as the one described in this project is an eye breaker to innovation because it is very flexible in design, material use, water rationing, and resilience building.

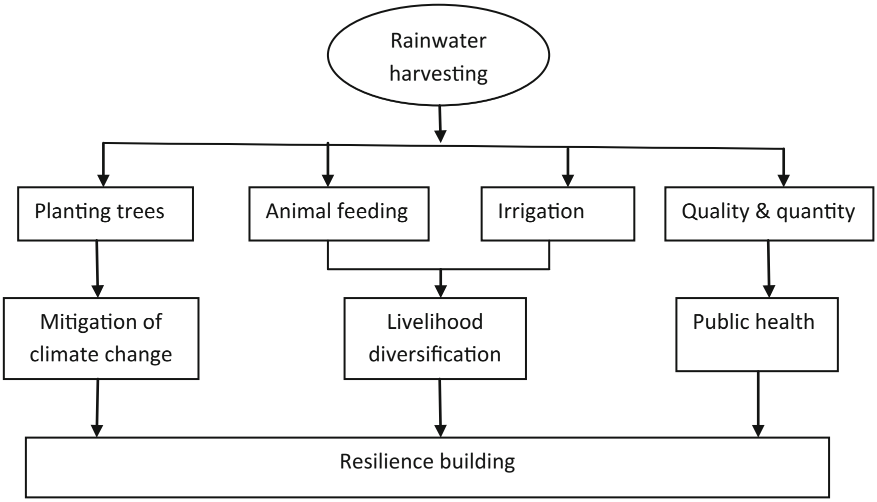


**Fig. 8** Integrated RWH model for pastoralist communities of Borena

### *3.3 Environmental Issues*

This project is environmentally friendly and does not pose any health or resource threats. The project focuses on climate resilience, diversification of livelihoods, and improvement of public health by the nature of its design and application. However, as it is hardly true to say that no project is without adverse impact, whenever an impact is anticipated, mitigation measures are also planned.

One of the adverse impacts could be utilization of space that otherwise could have been used for agriculture or grazing. But this is offset by a number of contingent plans such as:

- The space utilized for RWH is minimized by controlling evaporation and percolation and loss control in distribution.
- Installing the collection catchment at sites common to a group of people so that impact on one person might be shared.
- Optimize the productivity of the land by using drip irrigation from the collected water.

Another environmental impact could be the use of local trees or grass to construct the shade. This impact will be managed by substitution by planting new trees. The grass from the collection catchment and surrounding buffer zone can be used to replace what is used.

# 4 Conclusions and Recommendations

## 4.1 Conclusions

The use of rainwater harvesting has longer history in Ethiopia. With increasing scarcity of water resources, rainwater harvesting is an opportunity that many communities should not miss. Rainwater harvesting could even be the only option in many parts of Ethiopia particularly the pastoralist communities in Borena Zone.

Many rainwater harvesting technologies introduced so far failed to meet desired objectives and in some instances attracted unprecedented health problems. The pond program in Ethiopia is a good example. This has discouraged both the government and communities and donors. These days it is hard to get the acceptance of the pastoralist communities for traditional rainwater harvesting systems using ponds. On the other hand, pastoralist communities also have their own indigenous knowledge in storing water. However, with increasing water demand and decline in precipitation from time to time, it is critically important to think out of the box and introduce innovative ways of collecting rainwater.

The pilot rainwater harvesting system in Jimma was a good start to test the technology and proved to work that motivated the incubation of this system to the more needy pastoral communities in Borena Zone. However, there were peculiar features to be adapted when incubating the technology in Borena. The main technological differences entertained were:

1. Settlement pattern is different from Jimma (communities in Borena settle in clans as one family) and hence, individual household-based planning does not work.
2. As communities in Borena live in a harsher environment with lower precipitation than Jimma, two main strategies were followed. (1) Allowance for the collection surface area was given 20% more space than calculated and (2) integrated approaches that consider climate resilience and livelihood diversification potential of the technology was assessed and included in the design.
3. As pastoralists cannot detach themselves from cattle, the design considered 10 L per day for emaciated and young cattle.

## 4.2 Recommendations

1. Rainwater harvesting for pastoralist communities should meet minimum standards of quality and quantity to get the acceptance by the community.
2. The size of the rainwater harvesting to be introduced must have sufficient collection catchment and reservoir that can collect water to meet the needs of a group of families in a village.

3. The current incubated project needs to be scaled up considering the five design criteria but at a larger scale.
4. Practitioners in the field and donors should have an experience sharing forum to effectively engage themselves in rainwater harvesting.
5. Capacity building programs for pastoralist communities should be in place to empower them to introduce the new innovative technology.

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# The ‘Majaluba’ Rice Production System: A Rainwater Harvesting ‘Bright Spot’ in Tanzania

**John Gowing, Lisa Bunclark, Henry Mahoo and Frederick Kahimba**

**Abstract** The rainwater harvesting technique under consideration here is an example of intermediate-scale external catchment runoff harvesting. The focus for discussion is on the ‘*majaluba*’ system which is found in Tanzania and comprises a network of roughly level basins each surrounded by an earth bund. Basins are arranged in the landscape in order to collect local runoff from stony outcrops and grazing lands in upslope areas with cattle tracks often used as conduits. The ‘*majaluba*’ system is used primarily for the production of rainfed lowland rice. It has spread through autonomous diffusion of knowledge from farmer to farmer since its introduction in the 1930s. The estimated extent of this system is around 600,000 ha which contributes 60% of total rice production in Tanzania. This is a remarkable, but little known, success story, and represents a water harvesting ‘bright spot,’ where sustainable intensification of smallholder agriculture has been achieved at scale.

**Keywords** Agriculture · Sustainable intensification · Meso-catchment Runoff harvesting · Technology adoption

## 1 Introduction

Numerous authors have proposed definitions of rainwater harvesting (RWH), but there is generally very little difference between them. We adopt the definition proposed by Critchley and Scheierling (2012): ‘The collection and concentration of rainfall runoff, or floodwaters, for plant production.’ Similarly, many authors have

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attempted to classify RWH technologies into a broad typology (e.g., Boers and Ben Asher 1982; Gowing et al 1999; Oweis and Hachum 2009). A distinction is often made between techniques on the basis of where the runoff is collected and how far it is diverted. Runoff may be collected from fields, hillslopes, house roofs, rocks, pavements, roads and tracks, or ephemeral streams and gullies. Rainfall may be captured locally on the farm where it is to be used, or as runoff from rain that falls beyond the farm boundary which is then transferred to the farm over distances that vary from tens of meters to several kilometers. RWH practices may also be distinguished on the basis of how the captured water is stored; this is often within the crop's root zone, but may be in a storage pond (or tank) or in a shallow aquifer. We adopt the typology shown in Fig. 1.

The RWH technique under consideration here is classified as meso-catchment runoff harvesting. The *majaluba* (sometimes known as *majaruba*) RWH system is found extensively in Tanzania and is used primarily for the production of rainfed lowland rice in bunded basins. Hillslope runoff is collected from stony outcrops and grazing lands in upslope areas with cattle tracks often used as conduits (Fig. 2). It is believed to have originated in Sukumaland (Lake Victoria Basin) and is arguably not a 'traditional' practice, since it seems to have been introduced by Asian migrant workers during the colonial era (Shaka et al. 1996). It is a remarkable, but little known, success story—a 'bright spot' for RWH. Its adoption and spread without external intervention can be seen as indicative of the potential of appropriate RWH practices to deliver sustainable intensification of dryland cropping systems.

There are documented examples around the globe of agricultural innovations that have been effective in achieving positive impacts on rural livelihoods and food security (Pretty et al. 2006, 2011). These so-called bright spots provide evidence of successful adoption of novel agricultural practices at the level of the community (village, district, or catchment). Evidence from these documented bright spots contrasts with the general picture of agricultural stagnation in sub-Saharan Africa (SSA) (Wiggins 2014). As noted by NEPAD (2010), there is an urgent need to put in place a strategy to scale up these and other local-level successes in order to have a significant impact on the interrelated problems of land degradation, declining agricultural productivity, and rural poverty.

Pretty et al. (2006, 2011) reported analyses from 20 countries in Africa where sustainable intensification has been developed, promoted, or practiced. By early 2010, these projects had documented benefits for 10.4 million farmers and their families on approximately 12.7 million hectares. Their intention was to investigate the processes and outcomes on a large enough area and across enough farms to draw some common conclusions about how to develop productive and sustainable agricultural systems and how to scale these up to reach many more people in the future. Their 40 case studies represented various types of innovation and included a small number of examples of RWH.

The *majaluba* case study presented here can be seen as a contribution to the knowledge base on RWH 'bright spots,' where sustainable intensification of smallholder agriculture has been achieved at scale. We will describe the RWH

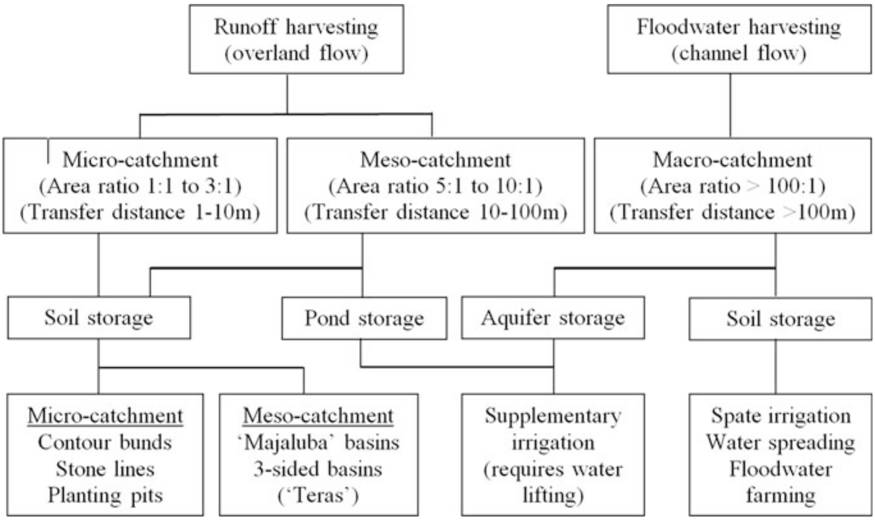


**Fig. 1** Typology of rainwater harvesting systems

system, review evidence of its expansion, and current extent and consider the importance of its contribution to rice production in Tanzania.

# 2 Methodology

## *2.1 Study Area*

The study area covered the central corridor of Tanzania (Fig. 2), which contributes 60% of the total rice production area (Government of Tanzania 2009). Three study sites were selected forming a northwest to southeast transect through the rice cultivation area. The most northern of the sites is Mwalogwabagore at approximately 30 km south of Lake Victoria in Mwanza Region and within the zone identified by Shaka et al. (1996) as being the origin of the *majaluba* system. Lali is located 200 km further south in Shinyanga Region and within the area described by Allnutt (1942). Lionii is close to the southern edge of the corridor at 60 km northeast of Dodoma and 300 km from Shinyanga.

The rainfall regime at the two northern sites is largely bimodal with a *Vuli* rainy season between October and December and *Masika* rainy season from March to May. Prolonged dry spells occur during January–February and a dry season during May–October. Average annual precipitation is between 800 and 900 mm. The most southerly site (Lionii) is located in the center of Tanzania, where there is a uni-modal rainfall regime with rainy season extending from October to April. Average annual precipitation in this region is less than 600 mm. All sites are in the

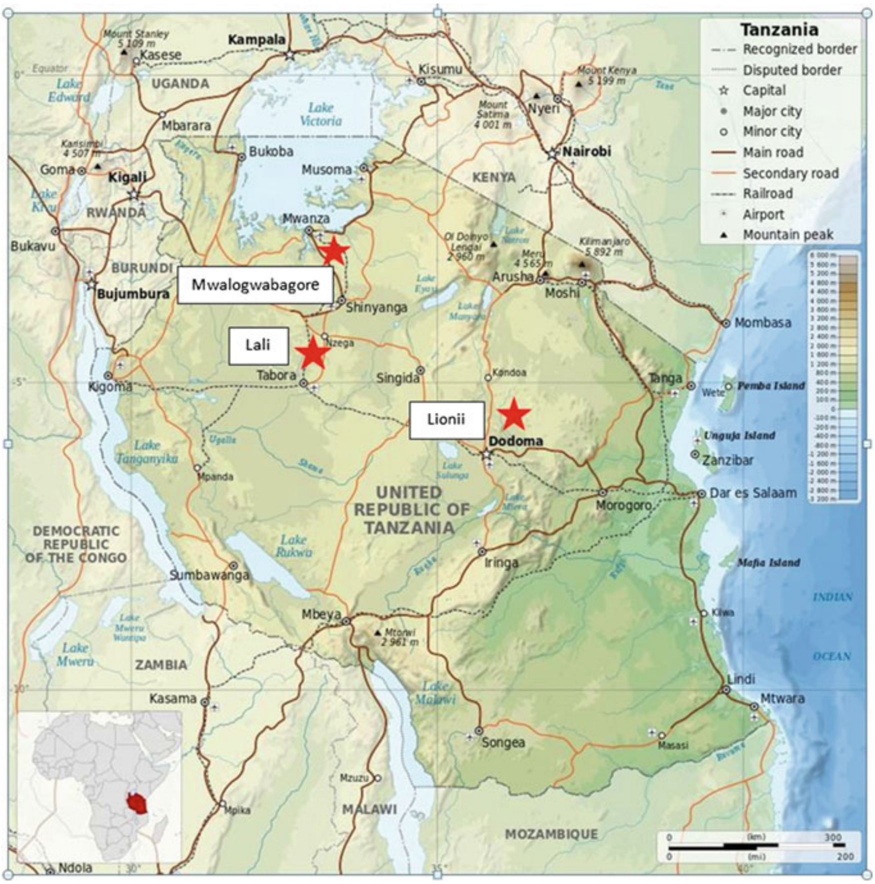


**Fig. 2** Map showing location of fieldwork sites in Tanzania. *Source* © Sémhur/Wikimedia Commons/CC-BY-SA-3.0 (or Free Art License)

central plateau physiographic region (at 1000–1300 m altitude) (Basalirwa et al. 1999).

The landscape comprises a sequence of valleys interrupted by granite hills with slope lengths 1–3 km in narrow valleys and 5–6 km in broad valleys. Soil types vary systematically in relation to physiography. Indeed, the concept of the soil 'catena' (soil sequence from hilltop to valley bottom) was first described by Milne (1947) in Sukumaland. Local farmers recognize this effect and local soil classification corresponds closely to scientific understanding (Payton et al. 2003). The typical Sukuma catena consists of freely drained sandy loams (Arenosols) on granite hills, followed by slowly permeable Planosols on the foot-slopes and swelling clay Vertisols in the valley bottoms. A description of these soils is given by Meertens et al. (1996), who emphasize the importance of the hard-pan soils which characterize the ‘cultivation steppe’ (as originally identified by Milne 1947). An idealized cross section of a typical catena is shown in Fig. 3.

## 2.2 *Prior Knowledge of the* **Majaluba** *Water Harvesting System and Its Evolution*

The existence of the *majaluba* rice system was first reported by Allnutt (1942) in the Sukumaland region of Tanzania (i.e., the zone to the south of Mwanza). He reported in particular on Shinyanga District in the south of the region, where the system had been recently adopted by farmers. He noted that, ‘ten years ago a rice grower in Shinyanga was almost a curiosity,’ but that rice was more established as an important crop elsewhere in the region. Clearly, there was evidence of adoption and spread at that time. This supports the report by Shaka et al. (1996) that the *majaluba* system originated in the 1930s when ‘a small number of Asian workers in the local [cotton] ginnery grew enough rice for their own purposes.’ They describe the situation in Maswa District, which is further north, closer to Lake Victoria and about 200 km from Shinyanga. Meertens et al. (1996) presented a comprehensive account of the historical development of farming systems in Sukumaland, which provides further evidence of continuing expansion. They cite Rounce (1951), who reported a survey conducted in 1945 which found that rice growing was expanding at that time. They cite also Collinson (1963) who reported the growing importance of rice cultivation during the 1950s. They report their own survey evidence from four ‘representative’ villages in Kwimba District (between Mwanza and Shinyanga), which shows that the increase in rice cultivation continued up to 1990.

As reported by Meertens et al. (1996), *majaluba* comprise roughly level basins surrounded by an earth bund that is typically 0.25–1.0 m high. Fields are positioned so that water for irrigation can flow by gravity through the system. They can be used for growing any crops with a high need for water, but in most cases paddy rice is cultivated. For rice cultivation, *majaluba* are usually built on hardpans or in valley bottoms on clay soils (known locally as *mbuga*). Water used in these systems is generally obtained (or harvested) from ephemeral streams, gullies, upslope land, or cattle tracks. Water enters the system through an inlet or opening at the uppermost basin and fills this before any excess is allowed to flow lower down the system in sequence (usually by overflowing the top of the bunds, or at a specific bund portion with lowered level). Rainwater in the *majaluba* system is also harvested in situ in case of little or no runoff from outside the fields. Farmers have developed an arrangement within the landscape (see Fig. 4) which aims to achieve a balance between upslope catchment area and downslope crop area. The catchment zone is typically heavily grazed, as this helps to generate runoff, but the slope length is limited in order to avoid excessive flow rates and erosion. On very long slopes, it is common to find two or more segments of bunded fields separated by catchment zones (Shaka et al. 1996).

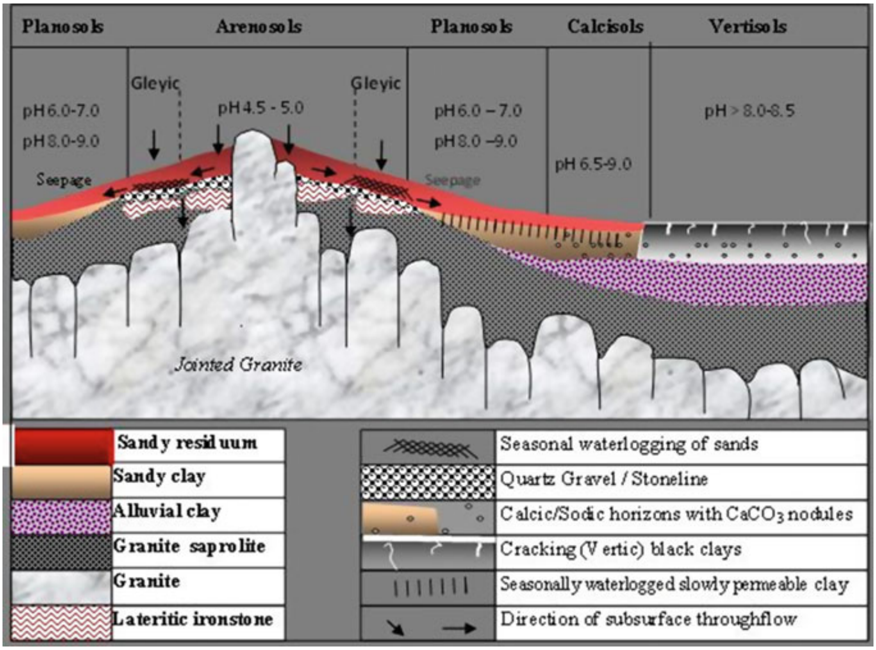


**Fig. 3** Idealized cross section of a typical soil catena. *Source* (Payton 2000)

**Fig. 4** View of *majaluba* water harvesting system. *Photograph* John Gowing

Farmers generally practice a mix of broadcast seeding and transplanting. As upper fields are the first to receive runoff, they often serve as nurseries and provide seedlings that can be used for transplanting and/or for gap filling in the lower fields. In good years, paddy yields of 2500 kg/ha are achieved, but water control is limited and in dry years some fields may remain fallow or may not provide a harvestable yield. Farmers generally aim to plant on the first rains, but if runoff is insufficient by December, it is unlikely that the crop will survive the January–February dry spells and in this case transplanting in March may be the best option (Meertens et al. 1996; Shaka et al. 1996).

## 2.3 Reappraisal Method

The purpose of the new appraisal was to gather empirical evidence that would allow us to explore whether the *majaluba* system has continued to expand beyond the extent reported by Meertens et al. (1996) and should indeed be viewed as a RWH ‘bright spot.’ Fieldwork was therefore conducted in Tanzania between September and October 2013 with the following research questions:

- Is the *majaluba* system still in use and still expanding?
- Where do farmers obtain technical advice on how to develop *majaluba*?
- What institutions are seen to influence the process of innovation?
- Is the change due to technology-push (e.g., technology promotion and performance) or demand-pull (e.g., need for more food, more money)?
- What factors exist to incentivize or constrain innovation?
- What are the impacts of this innovation on food and livelihood security?

Data collection at each site comprised participatory mapping and focus group discussions, transect walks, and key informant interviews. Separate focus groups (with twelve participants in each group) were held for men and women, in order to explore any gender-differentiated perceptions. Participants were chosen to represent households from a range of different socioeconomic, age, and livelihood groups with assistance from a local contact, which in most cases was the village (or hamlet) chairman. Farmers selected to participate were all heads of household or spouses; for the female focus groups, at least three participants in each were female heads of household. For the transect walk, five participants with in-depth knowledge of land-use patterns and land management of the village/hamlet were selected at each site. Key informants were identified via discussions with the village (or hamlet) chairman.

## 3 Results

### *3.1 Secondary Data on the Spread and Current Extent of the* 'Majaluba' *RWH System*

Official statistics provide an unreliable indication of the extent and importance of RWH in Tanzania. According to FAO (2016), the area of land equipped for irrigation increased from 20,000 ha in 1961 (i.e., at the time of independence) to 363,514 ha in 2012. The main irrigated crops are maize and paddy rice, accounting for about 38 and 22% of the irrigated area (FAO 2016). Other irrigated crops comprise beans, vegetables (including onion, tomato, and leaf vegetables), bananas, and cotton. The following types of irrigation schemes are reported:

- Modern irrigation schemes (55,229 ha) are formally planned and designed schemes with full irrigation facilities and usually a strong element of management by the government or other external agencies. Those schemes are developed in the regions of Kilimanjaro, Morogoro, and Mbeya.
- Traditional irrigation schemes (117,000 ha) have been initiated and operated by the farmers themselves, with no intervention from external agencies. They include schemes based on traditional furrow irrigation for the production of fruit and vegetables in the highlands and simple water diversion schemes in the lowlands for maize and rice.
- Improved traditional irrigation schemes (190,285 ha) are traditional irrigation schemes on which, at some stage, there was intervention by an external agency, such as the construction of a new diversion structure.

The definition of 'traditional irrigation schemes' is problematic, as it is not clear whether RWH systems are consistently included or excluded. National estimates are derived from a sample census considering less than 30% of all villages and the definitions used for irrigated land (e.g., related to rainwater harvesting) appear to be inconsistent. FAO (2016) reports a separate category of 'rainwater harvesting-based schemes' with a total extent 27,200 ha in 2001 with no recent data. These are described as schemes where mainly paddy rice is grown using rainfall captured directly in small bunded basins or runoff diverted from residential areas, paths, and transient streams. The source of this estimated area is unclear.

Statistics for rice production are also available from FAOSTAT[1] and RICESTAT[2] databases, and they provide a different picture. The area of rice production has expanded over the same interval from 82,000 ha in 1961 to 925,000 ha in 2015. The data show some volatility in recent years, but the total area harvested is now around 1 million ha. Expansion was steady up to 2000, reaching around 400,000 ha, but there has been rapid growth since then. Total production in

[1]http://faostat.fao.org.

[2]http://ricestat.irri.org:8080/wrsv3/entrypoint.htm.

Tanzania is now around 1.2–1.4 million tonnes per year of milled rice (Nkuba et al. 2016).

Three major rice production systems are recognized in SSA (Diagne et al. 2013): irrigated, rainfed lowlands, and rainfed uplands. Reported data for rice production are not disaggregated by production system; however, Diagne et al. (2013) were able to disaggregate data for 2009 based on a farm household survey. For Tanzania, they reported, respectively, 27, 72, and 1% of the total rice production area. Clearly, the so-called lowland rainfed production system dominates and a similar analysis by Balasubramanian et al. (2007) using data for 1995–2004 also shows 73% contribution from ‘rainfed wetland rice.’ The question is then: What proportion of this total area (i.e., around 650,000–700,000 ha) actually corresponds to the ‘majaluba’ RWH system?

## *3.2 New Insights into the Spread and Current Extent of the ‘Majaluba’ RWH System*

**Use of *Majaluba* RWH system**

Farmers in Mwalogwabagore and Lali reported that they were first exposed to rice cultivation by Asian migrant laborers in the early twentieth century. Farmers in Lionii adopted the technique in the 1980s after working in demonstration fields for an FAO project based in a neighboring hamlet (Bahi-Sokoni) around that time. In focus groups, farmers across all three sites said that they were driven to try the techniques as it allowed for converting previously unproductive land, largely used for communal livestock grazing, into highly productive cropland, providing both food and cash. The importance of rice production for income was said to have increased over the years, as explained in more detail below.

The whole family are involved in the cultivation of the paddy fields. Men tend to be responsible for preparing the fields for cultivation, clearing the land, building bunds, leveling the land, and plowing the soil ready for sowing/transplanting. Women were said to be primarily responsible for sowing seeds (either directly into the paddy field if broadcasting, or in a nursery bed if transplanting later), and weeding. Harvesting involves all family members. In all case study villages, farmers explained that most households tended to own a relatively large area of land in the lowlands, which was used for paddy cultivation. Typically, smaller areas of land were either owned or rented in the highlands to allow households to cultivate other staple crops, such as maize, sorghum, groundnuts, and cassava.

The arrangement of *majaluba* was said to be determined by the water availability and soil properties. Different-sized bunds are used to ensure that sufficient water for the crop is held, helping to prevent flooding or overdrying of the crop. Some fields depend on direct rainfall only, but most farmers channel rainfall runoff into their paddy fields where possible. Runoff is collected from the slopes above the *majaluba* fields, or from gullies carrying water from catchments in the uplands. In Lali, a few farmers were said to channel and store water in basins immediately upstream of their cultivated paddy fields, for supplementary irrigation. Some farmers with fields located in close proximity to the main road traversing Lali were also found to be diverting road runoff into their *majaluba* fields.

### History of *majaluba* RWH system

In the beginning, rice was cultivated in small depressions close to the house that collected water during periods of rainfall. As cultivation expanded, farmers sought larger areas of land where sufficient water and suitable soil were available for rice production, although still in relatively close proximity to the household.

> "This area is used for paddy as it got water from another stream and from an overflowing lambo (small pond)." (Transect walk, Mwalo)

In all sites, rice cultivation has expanded rapidly since its first adoption, with the emphasis on cultivation shifting from subsistence to commercial production in recent decades. Asset ownership and control was not observed to greatly affect the adoption of the *majaluba* system at household level. Adoption of the RWH technique was almost universal across households at each site. The majority of households at each site were said to own fields in the *majaluba* areas or were renting them if they did not. The arrival and spread of the ox-plow was said to be an important factor driving the expansion of *majaluba* in the mid-twentieth century across all sites investigated as it became quicker and easier to prepare the fields using ox-plow.

Declining yields from staple food crops, particularly sorghum and millet, also appears to have driven farmers to expand their cultivation of rice:

> "[In the past,] we had a lot of food from sorghum and millet and so not much need to grow paddy." (Key informant, Mwalo)

In contrast to sorghum and millet, the use of *majaluba* allowed farmers to make use of rainfall outside of their immediate location, which reduced water-related crop losses:

> "Paddy brings in a lot of harvest, 3-5 times sorghum… We adopted it as we cannot depend on the rains and the upland crops but the gully brings in water from Kondoa, therefore [good] yield and production is more assured [in paddy fields]." (Men's Focus Group, Lionii)

Good markets for rice enabled farmers to turn previously unprofitable land into highly profitable paddy fields. Farmers reported that it is due to the relatively high selling price of rice that it has become the main cash crop for most households in their regions in recent decades. Poor market performance of sorghum and cotton, which were previously the main cash crops for these households, was reported to have fueled further the expansion of rice.

> "[We] changed from sorghum as it has no market value and we do not like the taste of it. We are not cultivating cotton much anymore as it is expensive to produce and has no market value… Cotton production started to reduce from [the year] 2011, as then was when

> its price decreased. We cultivate other crops where we used to cultivate cotton … Cotton used to be the main cash crop before rice."(Men's Focus Group, Lali)

> "[Rice cultivation expanded] because of business growth. We use rice as a cash crop instead of cotton [because] the price of cotton dropped and the market is not stable." (Men's Focus Group, Mwalo)

> "Before rice, sorghum and cassava were the main crops. Cotton has gone down in price so few people cultivate it." (Transect walk participant, Lali)

Aside from markets, social attitudes have also encouraged the expansion of rice cultivation. An increasingly favorable attitude toward rice led to increased adoption, as people's eating preferences turned from sorghum toward rice. This was thought to be due to the perception that eating rice represented a higher level of social standing, which reflected changes in eating habits in other areas of the country.

Information from the respondents indicated that external intervention has been minimal, with adoption spreading spontaneously through autonomous diffusion of knowledge from farmer to farmer. After learning the basics of rice cultivation from Asian migrant workers in Mwalogwabagore and Lali, farmers indicated that agricultural extension officers provided their main source of knowledge and support. Extension staff were said by farmers and key informants to have provided training and advised them on a range of agronomic practices, including changing from broadcasting to transplanting and leveling fields, for example. However, many farmers also said they 'found out for themselves,' which suggests that a process of trial and error may have also had a role to play. No specific projects or interventions relating to *majaluba* were conducted in any of the case study villages, but some farmers spoke of activities conducted in nearby areas that they saw or worked on.

In Lali, some selected farmers had traveled for training on rice cultivation and *majaluba* given as part of regional and national initiatives. For example, one key informant mentioned three farmers from Lali and two other hamlets in the area received two sessions of training at the Kilimanjaro Agricultural Training Centre in the late 1990s and early 2000s. The purpose was for these individuals to act as 'champion farmers' and share their knowledge with others upon their return. On the whole, evidence from focus group discussions suggested that in most cases this did not happen, although one farmer is said to have formed a working group of approximately five farmers to allow him to share the knowledge he obtained.

Although not direct recipients of external intervention, farmers in Lionii were able to use knowledge from projects implemented in neighboring settlements to both adopt and improve the *majaluba*. A later FAO project in neighboring Bahi-Sokoni was said to have been used as the basis for organizing the *majaluba* system in Lionii:

> "In Mashamba Mapia [area] there are good yields as this is the area with new fields where the layout was made with assistance from FAO, they drew a sketch plan of how fields and canals should be laid out in Bahi-Sokoni and we used this in Lionii [too]." (Key Informant, Lionii)

In contrast to the other two case study sites, farmers in Lionii spoke of the lack of support provided by agricultural extension staff in their hamlet, both for rice cultivation and other crop production activities.

**Livelihoods and paddy cultivation**

Not only do *majaluba* provide a way for farmers to benefit from rainfall runoff, they also provide flexibility and hence reduce farming (and therefore livelihood) risks. Farmers in Mwalogwabagore and Lionii spoke of the variation that occurred in area of paddy cultivated depending on farmers' perceptions of rainfall that would be received in a given year.

> "Once it starts raining we prepare the rice fields. There was not enough rainfall last year so not all paddy fields were cultivated…. areas cultivated were those with water, this water came from the dam in another village that overflowed. Those that did not cultivate did not get water from this. The area cultivated [in the paddy] depends on the rainfall each year." (Transect walk participant, Mwalo)

Data suggest that one of the reasons that *majaluba* have been so successful in the case study region is that the system is complementary to existing livelihood practices. *Majaluba* were said to be prepared in the month of October–November, after seeds for other staple crops, including maize, cassava, and millet, had been sown. See cropping calendar (Fig. 5).

However, the benefits of *majaluba* were not equally distributed among households. Access to and control over land and water was not equal across all *majaluba*. In general, those farmers who were closest to water sources, in the upslope areas of the lowlands, had better access and control. Downstream farmers were said to only have access once those upstream had finished irrigating their fields, in many cases relying solely on overflows from fields above. The lack of governance arrangements was said to lead to conflicts between upstream and downstream farmers in all sites. In Mwalogwabagore, there were reports during the transect walk and focus groups that some farmers with downstream *majaluba* sometimes made the decision not to cultivate in a particular year if the rainfall was not considered favorable, as the risk of insufficient water to meet crop demand was too high.

Rice is seen as both a food and cash crop by farmers. In most cases, the data indicate that use of *majaluba* has provided an additional source of food for households, both directly and indirectly. A proportion of rice (typically 30%) is reserved for household consumption, which is usually a different variety from the rice that is destined for sale (this is because farmers do not find the rice that reaches the highest price in market to be palatable). The outcomes of a ranking exercise conducted during focus groups in all case study sites suggest that rice provides a greater contribution to household food provisioning in Lali and Lionii compared to Mwalogwabagore, with rice ranked first/second and fourth most eaten crop, respectively. When sold, profits from rice were also used to purchase additional food crops, particularly maize, which is said by farmers to be increasingly difficult to cultivate due to changes in rainfall. It is not clear what overall impact the rice has had on food security levels across households, but in general it seems that

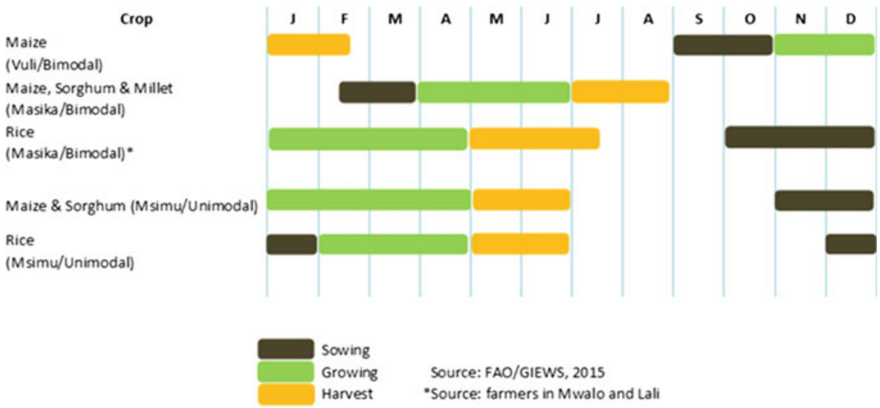


**Fig. 5** Typical calendar for staple crops in Tanzania for regions with bimodal rainfall (Mwalogwabagore and Lali) and uni-modal rainfall (Lionii)

households are still not food secure. Aspects such as poor management of harvest and low rainfall still lead to food insecurity in some years:

> “They reduce the amount of crop buyers to stop people selling so much food.” (Key Informant, Mwalo)

It is not clear to what extent the adoption of paddy cultivation using *majaluba* has offset reductions in yields from traditional food crops, including maize and sorghum. The *majaluba* system was said to help ensure good yields despite unreliable rainfall through the harvest of runoff from surrounding land or ephemeral streams and storing it within bunds. Yields in fields where farmers were harvesting and storing water were said to be higher compared to fields where they were relying on direct rainfall only.

Paddy provides a valuable contribution to household incomes across the case study sites. It was said to be the main cash crop in Mwalogwabagore and Lionii and second largest cash crop (after cotton) in Lali. Aside from the purchase of food, income from the sale of paddy is also used to meet wider household needs, such as education and healthcare costs. However, at the individual level, paddy provided a much greater contribution to men’s income compared to women’s, who relied more on the cultivation of horticultural crops and other non-agricultural activities for their income. Daily labor on other farmers’ paddy fields provided a source of income for both men and women in some (poorer) households. However, regardless of large areas of paddy production and significant contribution to income it provided, households continued to be engaged in a range of other on- and off-farm agricultural activities, including non-farm casual labor and masonry for men, and charcoal preparation and sale of firewood for women.

Although data suggest that one of the reasons that *majaluba* have been so successful in the case study region is that the system does not conflict with existing livelihood practices, there was some evidence to suggest that households where livestock comprised a greater proportion of income than agriculture were negatively impacted by the expansion of *majaluba*, particularly in Lionii. This impact is largely due to the transformation of land that was previously used for grazing into paddy:

> "All of this area [now cultivated] was used for grazing before it was paddy fields. Now the grazing area used is 6 km away." (Transect walk, Lionii)

> "In the past many had livestock, but the grazing land has become scarce so these people decided to move away." (Key Informant, Lionii)

## The future for *majaluba* RWH system

Farmers were found to be continuing to cultivate paddy and to look for areas to expand rice production further. In all study sites, the only constraint to the adoption and expansion of the *majaluba* system by farmers appeared to be a lack of appropriate land or ability to rent it. In Lali, fields that were previously used to cultivate maize, cotton, groundnuts were now being converted to paddy fields:

> "Rice cultivation started in the area along the railway as this is mbuga [clay] soil and it has access of runoff from the railway. Before we grew sorghum here and the same in the other fields [now used for paddy]." (Focus Group, Lali)

The reason for this change in crop was said to be due to low yields from sorghum and maize production in these areas, which suggests that *majaluba* provide an effective way for farmers to cope with changing rainfall in the region:

> "Paddy has expanded over the years, before paddy [farmers here] grew sorghum and maize [in these fields], but if they did not get a yield from one of these, they thought then, why not try paddy?" (Key Informant, Lali)

In general, there was said to be a growing scarcity of suitable land and farmers had limited possibilities for further expansion of paddy in their own villages/hamlets. Farmers were found to be renting additional land in neighboring hamlets and villages to enable expansion of production. In some cases, farmers were able to rent or purchase areas that were highly suitable for paddy production, but in some cases land scarcity led farmers to cultivate in less-suitable areas:

> "Some farmers are trying to expand [paddy], but into the wrong type of soil and so they have a high seepage and water loss problems." (Transect walk, Lali)

Farmers felt that soil infertility (due to lack of manure and fertilizer) was also responsible for limiting yields obtained in some areas, although in fields recently brought into cultivation this was not often an issue. According to key informants, lack of knowledge on optimal agronomic practices also limited yields for many farmers. This could be exemplified by farmers practicing agro-pastoralism, yet not carrying animal manure to their fields.

Focus group discussions indicated that access to and control over runoff was a key factor determining yields and would remain so into the future. Those with good access to runoff from gullies or surrounding land obtained higher yields than those located further away from runoff sources, or relying on direct rainfall only. There was a high level of competition to secure access to a field with a good runoff source, and not all farmers had the financial capital to rent fields considered to receive higher levels of runoff.

## 4 Discussion: Does the ‘*Majaluba*’ System of Rice Production in Tanzania Represent a RWH ‘Bright Spot’?

Based on recent investigations in seven countries in SSA, Critchley and Gowing (2012, p. 190–191) concluded that ‘bright spots’ are evident where RWH technologies have been successfully adopted at scale; however, data collection on their extent and impact continues to be inadequate. This analysis of the situation in Tanzania, based on the transect survey together with secondary data, indicates that the contribution of the *majaluba* RWH system to the growth of rice production in Tanzania is clearly very considerable, but available data do not reflect this reality. The RWH data problem is once again evident.

National data for rice production in Tanzania are not disaggregated by agroecological system and do not differentiate RWH systems. However, survey-based approaches (Diagne et al. 2013; Balasubramanian et al. 2007) have consistently demonstrated that the lowland rainfed production system represents around 70% of the total paddy production area. Not all is under *majaluba*, but survey evidence for Shinyanga Region (Nakano and Kajisa 2013) shows that this RWH system dominates there with 95% of rainfed paddy fields recorded as being bunded. Results of our transect survey through the central corridor confirm that lowland rainfed production is largely synonymous with adoption of the *majaluba* RWH system. A plausible estimate for the current total extent of the *majaluba* system in Tanzania is therefore around 500,000 ha from the central corridor alone and perhaps 600,000 ha across the whole country.

The results from this case study in Tanzania raise questions about transferability of the experience and the potential of mesoscale RWH techniques for sustainable intensification of agriculture more widely in SSA. What can be concluded about the drivers of adoption? Successful adoption of soil and water conservation measures in SSA drylands has been attributed to: household and farm characteristics, knowledge of technical innovations and external assistance, characteristics of the measures (labor demand, tangible benefits, etc.), stakeholders’ perceptions, and impetus for diversification of farmers’ incomes (Sietz and van Dijk 2015).

Evidence from the transect survey confirms the attractiveness of the *majaluba* rice system compared to alternatives available to smallholder rainfed farmers, as also reported by Hatibu et al. (2006) from a survey in Maswa District (Sukumaland). They reported a survey of 120 farmers using recall data for a period of six years and showed that the *majaluba* rice system performed best. Productivity of land was US$400–600 per hectare, and productivity of labor was US$10.5–12 per person-day. Follow-up monitoring of 90 farmers for two years confirmed this performance estimate with paddy yields recorded at around 4000 kg/ha. Plausible estimates therefore suggest that average yield for *majaluba* is around 2500 kg/ha, which might drop to 1500 kg/ha in a poor rainfall year and might increase to 4000 kg/ha in a good year as reported by Meertens et al. (1999).

It is clear that physical environmental characteristics may also influence performance and therefore successful adoption. Suitability depends on the following: rainfall, slope, soil type, soil depth (Bulcock and Jewitt 2013). It is tempting to propose that the success of the *majaluba* system is attributable to favorable landscape and soil conditions (e.g., hard-pan soils), but the extent of its range across the central plateau of Tanzania and reaching at least 1000 km from its origin indicates that it is suitable for a range of environmental conditions.

The transect survey has shown that farmers view rice as a dual-purpose crop with part (typically 30%) retained and consumed in the household and the remainder providing cash income. Not only does the *majaluba* RWH system provide a way for farmers to benefit from rainfall runoff, but it also reduces farming (and therefore livelihood) risks. It adds to household resilience in that its adoption does not conflict with existing livelihood practices and the choice of either retaining for household consumption or selling for cash provides livelihood flexibility.

Across SSA, the large majority of farmers do not have access to irrigation and in the future the great majority of farm families will continue to rely on rainfed agriculture for their livelihoods. Recent analysis (Ward et al. 2016) indicates that in only nine countries can irrigation be developed for more than 20% of the dryland cropped area (27% in Tanzania). The challenge of meeting future food security will depend on improving rainfed production through adoption of RWH (Rockstrom and Falkenmark 2015). The evidence reported here for a RWH ‘bright spot’ is important in this context, not least because the *majaluba* system has spread through autonomous diffusion of knowledge from farmer to farmer with minimal external support. Rice production is a focus for the Government of Tanzania on its ‘Big Results Now’ (BRN) initiative, but it is notable that the role of RWH is not mentioned and the focus is entirely on irrigated rice production (GoT 2015). There is a strong case for BRN to recognize the RWH ‘bright spot’ and build on its success.

## 5 Conclusions

An analysis of the available secondary data supported by a 600-km transect survey across the dominant rice production zone in Tanzania has demonstrated the importance of the lowland rainfed production system and the preeminence of the ‘majaluba’ RWH system. This system comprises a network of roughly level basins each surrounded by an earth bund and arranged in the landscape to collect local runoff from stony outcrops and grazing lands in upslope areas with cattle tracks often used as conduits. We estimate that the 'majaluba' system contributes about 60% of total rice production in Tanzania.

It is clear from the transect survey that the influence of external assistance has been minimal and the continuing expansion over eight decades and over a vast distance has been driven by autonomous diffusion of knowledge from farmer to farmer since its introduction in the 1930s. Rice production is not a traditional farming practice in Tanzania, but transfer of knowledge has not been a constraint to its adoption by 200,000–300,000 users. It is an appropriate technology that has allowed farmers to respond to opportunities provided by (i) the availability of the ox-plow which reduced the labor constraint on developing new land and (ii) the expanding market within Tanzania for rice which provided an attractive substitute for other cash crops while also allowing for household consumption as a staple food crop.

The *majaluba* system is an example of intermediate-scale external catchment runoff harvesting. This brings the advantage that fields can be developed by individual farmers who nevertheless still gain from runoff generated from a wider area of land. However, the ease of individual adoption and absence of formal water-user organizations may be seen as a constraint on sustainability. It can be seen that conflict between farmers over access to scarce water does occur. There is a case for external intervention to strengthen governance arrangements.

Nevertheless, the success of the *majaluba* water harvesting system in Tanzania is remarkable. It clearly represents an example of a successful agricultural innovation and is without doubt a water harvesting 'bright spot' with potential for transfer to other parts of SSA.

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# Fostering the Adoption of In Situ Rainwater Harvesting for Food Security in Rwenzori Region, Uganda

**James W. Kisekka, Nasser Kinaalwa, Evelyne Busingye and Maarten Onneweer**

**Abstract** In situ rainwater harvesting is recognised as a key strategy to improve agriculture production to ensure food security, and several techniques exist that have proved successful in improving soil water storage and fertility. However, widespread adoption of these techniques is hampered by absence of adequate quantifiable evidence of their impact as well as a limited understanding of the determinants of adoption. This paper presents the impact of simple in situ rainwater harvesting techniques and explores some of the factors that led to better adoption of such techniques, based on a case study from Rwambu region in Uganda. It concludes that the adoption of the interventions is affected by current productivity of the land or availability of other land for farming, available resources and their competing uses, labour constraints and past approaches for promoting the interventions.

**Keywords** Soil water storage · Impacts · Adoption drivers · Land productivity

## 1 Introduction

Water availability is the major limiting factor to improved crop yields in Sub-Saharan Africa, particularly the absence of water during critical growing stages (Barron and Okwach 2005; Fox et al. 2005). This is due to highly variable rainfall, frequent drought and low water productivity (Critchley and Gowing 2012). A solution lies in managing rainwater on farmer's fields, also known as in situ rainwater harvesting (Ngigi 2003; Vohland and Barry 2009; Critchley and Gowing 2012; Mekdaschi and Liniger 2013).

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In situ rainwater harvesting has widely been accepted as a solution to increase crop production under water-stressed situations and societies all around the world identified simple technologies to harvest additional water for crops (Critchley and Gowing 2012; Mekdaschi and Liniger 2013). In all cases, these technologies, when properly implemented, positively impact the soil conditions (Ngigi 2003; Vohland and Barry 2009). Particularly in arid and semi-arid areas, the potential to improve and sustain crop production through conservation agriculture and in situ rainwater harvesting and management technologies has received wide recognition (Critchley and Siegert 2001; Ngigi 2003). With the increasing unpredictability of the rainy season, possibly a result of changes in climate patterns at local and global scales, in situ rainwater harvesting becomes even more paramount. Increasingly, there is too much water over a short period of time during the rainy season resulting in flash floods, followed by acute water shortages after the rains (see for instance Osbahr et al. 2011). Knowing this, we find in our work that the replication and transfer of in situ rainwater harvesting technologies is hampered by limited transfer of knowledge from one area to another and limited understanding of their impact, for instance on crop yields (and therefore linkage to food and livelihood security), and what influences uptake by farmers.

In rural development theory, there has been a prolonged debate about the structural factors that make people intensify their agricultural system. The work of Boserup (1965) stands out as the canonical work that described how increasing pressure on the land would actually lead farmers to intensify their agricultural systems, often with in situ rainwater harvesting practices. Since then, it has often been shown how smallholder farmers and pastoralist have successfully applied in situ rainwater harvesting techniques to mitigate the impact of drought, thereby improving production (Tiffen et al. 1993; Fox et al. 2005; Hatibu et al. 2006; Mwangi and Rutten 2012). These technologies include the usual *fanya juu* and *fanya chini* trenches, zai pits, and mulching and stone bunds. In southern Kenya, these technologies were introduced through colonial forced labour, rejected and later picked up again (Tiffen et al. 1993). In some areas of Ethiopia, scale adoption was enforced by food for work schemes or forms of involuntary labour (Descheemaeker et al. 2010). For Uganda, NEMA (2001) reports that various soil conservation technologies (for instance terraces, contours, trenches, agroforestry, and strips of napier grass planted along contours or on terraces) were introduced to control soil erosion in highland areas. Barungi et al. (2013) indicate that the technologies have been promoted by both governments, (through Ministry of Agriculture, Animal Industry and Fisheries (MAAIF)) and Non-Governmental Organizations. However, uptake of the technologies remains low (Barungi et al. 2013).

In 2015, a lack of systematic reviews of literature on the impact of water harvesting technologies on crop yields prompted Bouma et al. (2016) to conduct a meta-analysis of the available literature. Even though Bouma et al. (2016) found that water harvesting causes a significant increase in crop yields, the researchers recommended that more work needs to be done to strengthen the scientific knowledge base. This paper provides more information on the impact of in situ rainwater harvesting on crop yield and also the determinants of adoption of such interventions. In this paper, we provide reference material and inspiration for organizations and individuals looking to promote in situ rainwater harvesting amongst communities and other players. At the same time, we propose that in situ water harvesting is not a one size fits all solution, people and lands are different, even within the same district. Therefore, the replication and transfer of in situ rainwater harvesting technologies needs an understanding of the kind of agriculture people already practice, the possibilities of the land, and the needs and demands of the people.

# 2 Study Area and Methods

## *2.1 Study Area*

Rwambu is a transboundary wetland separating the sub-counties of Nyabbani and Kijjongo of Kamwenge and Ibanda districts, respectively, in the Rwenzori region of western Uganda (Fig. 1). The area receives bimodal rainfall of more than 1000 mm a year and has a tropical climate. The Rwambu wetland and its catchment drain into

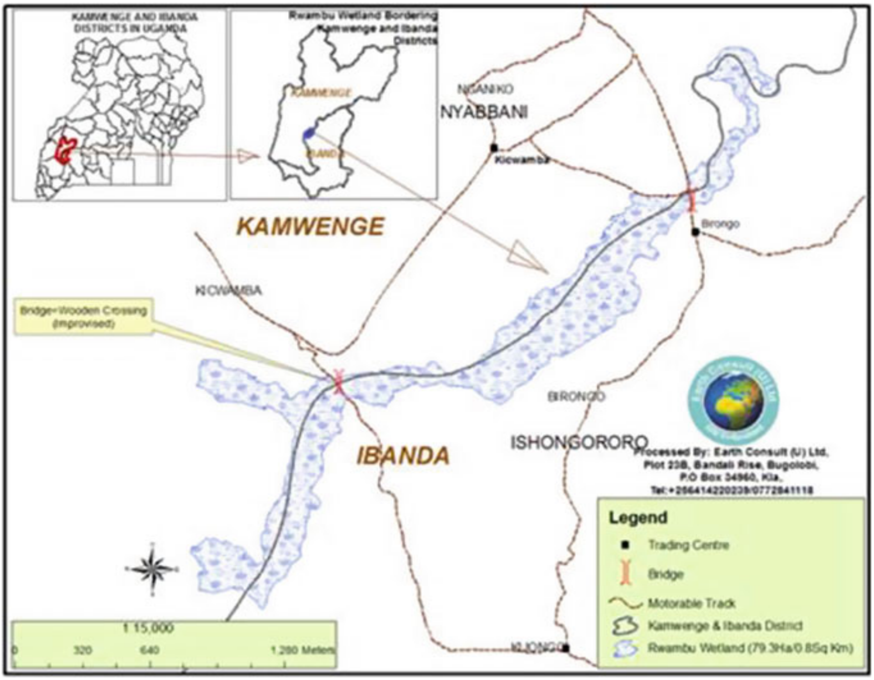



**Fig. 1** Location of Rwambu, Uganda

a stream called Rwambu, which drains into a bigger river called Mpanga that in turn drains into Lake George.

Prior to 2012, the Rwambu area faced several interconnected challenges, such as encroachment on the wetland for crop farming, local community reports of reduced soil fertility on the slopes and reduced dry season yield of boreholes. Kisekka (2015) reports as follows how community members described the changes in their community. As population increased, farmers started to cultivate on the hillslopes but without any soil conservation measures therefore leading to soil erosion. Fertile soil eroded from the hillslopes silted up the wetland. As the hillslopes became less productive for crop farming, farmers started to cultivate in the wetland, often saying they were "following their fertile soils". Kisekka (2015) adds that because of increased run-off generation on the hillslopes, the water would rush downhill without sufficiently infiltrating the ground. This resulted in a reduced water table and consequently the drying of springs and boreholes on the hill slopes (Kisekka 2015).

## 2.2 Methods

In 2012 RAIN, Joint Effort to Save the Environment (JESE), Wetlands International, local governments and communities in the project area, with financial support from the Dutch WASH Alliance, started a pilot project. The pilot aimed to test an integrated approach to in situ rainwater harvesting, wetland protection and water sanitation and hygiene (WASH) service provision at landscape level in Rwambu area. More specifically, it aimed to demonstrate how wetland restoration and management coupled with in situ rainwater harvesting could be integrated at catchment level to sustain WASH. The in situ rainwater harvesting interventions promoted by the project are gathered under the acronym 3R which means that the interventions contribute to recharge, retention and reuse of rainwater. An example can be found on Figs. 2, 3, 4, 5 and 6. The component of 3R technologies aimed to reverse the degradation previously caused by soil erosion on the hilly stony slopes, prevent further soil erosion and improve soil moisture recharge and retention. The 3R technologies implemented include grass strips, *fanya juu* and *fanya chini* terraces and stone bunds. Besides in situ measures, several other technologies such as gully plugs, small check dams and infiltration pits were established to improve water infiltration into the soil.

*Fanya juu* and *Fanya chini* are earthen bunds made by excavating a trench and making ridge along the contour. To build a *Fanya juu* terrace, soil dug from the trench is put upslope of the trench, and for *Fanya chini*, the soil is put downslope of the trench. Stone bunds, on the other hand, are lines of stones placed along the contour. Stone bunds are usually constructed using both small and large stones (smaller ones placed upslope and larger ones downslope) but can be made entirely of small stones. A grass strip is a row of grass (about 1 m wide) along a contour. The grass can either be planted or be a deliberate remainder when the land

**Fig. 2** A farmer stands at a *fanya juu* in a banana plantation. *Photo* James W. Kisekka

**Fig. 3** A newly constructed stone bund. *Photo* James W. Kisekka

is prepared for crop farming. The interventions were implemented sometimes using local hired labour but increasingly through voluntary community participation. Table 1 summarises the volume of work per intervention implemented.

**Fig. 4** A check dam in a banana garden. *Photo* James W. Kisekka

**Fig. 5** A *fanya chini* is a coffee–banana garden. *Photo* James W. Kisekka

Anticipating that the structures would indeed impact ground water levels positively, changes in the groundwater table were measured. Measurements were done periodically in a borehole, which had broken down and consequently abandoned because its yield had dropped greatly over the years.

**Fig. 6** A percolation pit in a coffee garden. *Photo* James W. Kisekka

**Table 1** Volume of work per intervention

| Technology | Volume of work |
|---|---|
| Tree planting | 50,000 and 75,000 $m^2$ covered on top of the hill and along the wetland, respectively |
| Grass strips | 800 m, total linear length |
| Grass bunds reinforced with small stones* | 40 m, linear length |
| Percolation pits | 10 pits |
| Fanya juu and Fanya chini bunds | 6000 m, total linear length, 4000 m of which collect run-off from roads |
| Check dams | three check dams, each 12 m long |
| Stone bunds | 4000 m, linear length |

*Source* Adapted from Onneweer (2014a)
*Inspired by complaints from women that big stones (to make stone bunds) were too heavy for them to carry

Further, twenty-seven farmers who had established in situ rainwater harvesting interventions on their gardens were purposively selected for this research. In addition, we randomly selected 14 farmers who had not established in situ water harvesting interventions as a control group and to establish the reasons for not implementing the interventions. The farmers were interviewed in November 2015, using a semi-structured questionnaire.

Farmers with in situ rainwater harvesting interventions on their gardens were asked (amongst other things):

(a) which interventions they have on their gardens (type and extent in terms of metres were applicable),
(b) what was the productivity of their gardens before and after the interventions were implemented,
(c) the main source of labour they used to implement the interventions

(d) challenges they faced in implementing or managing the interventions.

To know which other factors might have influenced crop yields, the farmers were asked to describe how they managed their gardens before and after the interventions were implemented.

Farmers without in situ water harvesting interventions were asked:

(e) if they knew any water buffering interventions (types and main purpose)
(f) reasons for not implementing the interventions.

In addition to the farmers, four key informants (local leaders) were asked their opinion on the determinants of adoption of the interventions in the area. Further information on (changes in) the project area was drawn from reports, publications and online articles by the authors of this paper or their colleagues. This paper also presents farmers' voices as case studies (although farmers' names are not mentioned), with an aim to keep the testimonies original to the extent possible.

## 3 Results and Discussion

This section describes the implementation of interventions and the actual impacts reached. We then enter into a discussion on the constraints in the uptake of in situ water harvesting. The section closes with a number of testimonies of farmers who implemented in situ water harvesting measures.

### *3.1 Interventions on Farmers' Gardens*

The farmers established either trees, check dams, percolation pits, stone bunds, grass strips, *fanya juu* or *fanya chini* trenches depending on the location of their gardens along the slope. The measures such as percolation pits and check dams could not be positively correlated to crop yields. Farmers have only one or two check dams or percolation pits on their land, and these are often far apart, making it difficult to correlate impact and interventions with reasonable confidence. The project did not combine trees with crops (agroforestry). Therefore, this paper

**Table 2** Type and extent of interventions on farmers' gardens

| Type of intervention | Number of farmers ($n$ = 27) | % of farmers ($n$ = 27) | Average number per intervention | Average length per intervention (m) |
|---|---|---|---|---|
| *Fanya chini* | 23 | 85 | 4 | 21 |
| Stone bunds | 1 | 4 | 8 | 15 |
| Grass strips | 3 | 11 | 3 | 13 |

focusses on stone bunds, grass strips and *fanya chini* terraces. Table 2 provides an overview of the interventions and the number of farmers who implemented them.

To implement the water buffering interventions in their fields, the selected 27 farmers used project-provided labour, their own labour, hired labour or a combination of own labour and hired labour (Table 3). Project-provided labour and own labour were the highest sources of labour, in equal proportion (37%).

Out of the 10 farmers to whom the project provided initial labour, we learned that 70% of them further replicated the interventions using other sources of labour, mainly own labour (Table 4).

## *3.2 Impacts*

### 3.2.1 Crop Yields

Of all farmers interviewed, only 4% stated they did not notice a change in crop yields after the in situ interventions were implemented and this perceived lack of impact only applied to the farms where grass strips were implemented. The rest of the farmers observed a 40–60% increase in crop yields depending on the interventions (Table 5). The farmers interviewed indicated that the only change to the management regime of their gardens was the introduction of the water harvesting interventions. Other factors such as the frequency of weeding and fertiliser use remained approximately the same. Therefore, it may be concluded that the difference in crop yields can be attributed primarily to the in situ rainwater harvesting interventions.

The increase in crop yields was caused by improved soil moisture especially during the dry season as well as reduced erosion of fertile topsoil during the rainy season. We found confirmation of erosion (and how to reverse it) at some of the

**Table 3** Sources of initial labour

| Source of initial labour | Number of farmers ($n$ = 27) | % of farmers ($n$ = 27) |
|---|---|---|
| Project | 10 | 37 |
| Own labour | 10 | 37 |
| Hired labour | 5 | 19 |
| Both own labour and hire labour | 2 | 7 |

**Table 4** Source of labour after project support

| Source of labour | Number of farmers ($n$ = 10) | % of farmers ($n$ = 10) |
|---|---|---|
| Own labour | 5 | 71 |
| Hired labour | 2 | 29 |

**Table 5** Average crop yield improvement per intervention

| Intervention | Crop | Number of farmers ($n$ = 27) | % of farmers ($n$ = 27) | Increase in yields (%) |
|---|---|---|---|---|
| *Fanya chini* | Banana | 10 | 37 | 59 |
| | Coffee | 13 | 48 | 56 |
| Stone bunds | Beans | 1 | 4 | 60 |
| Grass strips | Coffee | 2 | 7 | 41 |
| | Beans | 1 | 4 | 0 |

stone bunds which were built one metre high but filled up with fertile soil, eroded uphill, in just one rainy season.

Even where the increase in yield may not be substantial, any minimal increase means an extra income to the farmer, provided the cost of implementing the measures is not prohibitive in terms of time. The farmer can implement the measures himself, but if he or she needs to hire labour, then the increment in yields could mean the farmer can have an extra income to pay the labour (if the labour is not too expensive, and usually it is not).

### 3.2.2 Groundwater Level

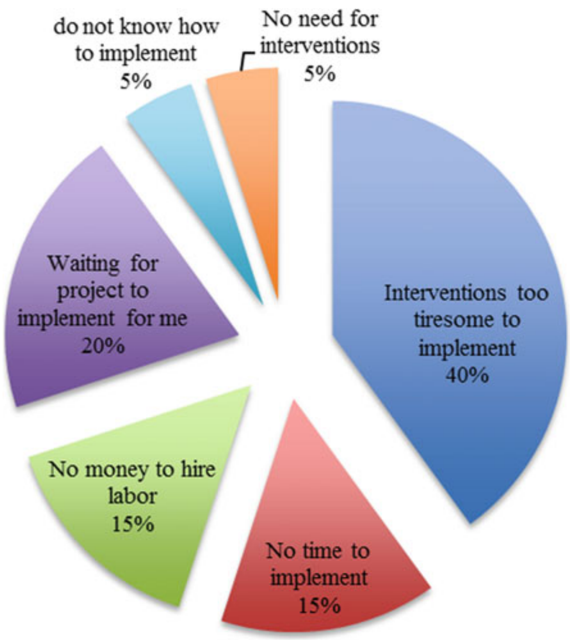
Another important impact of the in situ measures in Rwambu was the improved ground water levels in the project area compared to neighbouring villages. At the end of the project implementation, the yield of boreholes and shallow wells in other villages reduced during the dry season of June–September. In Rwambu, the water table increased a total of 2 m in 2 years after the implementation of water harvesting interventions (Onneweer 2014b). The improving water table inspired repairs of and piloting "pay-per-fetch model" on the previously abandoned borehole. Now, the community buys clean water from the borehole at 0.03 EUR instead of buying clean water expensively at 0.15 EUR from water vendors or using dirty water from unprotected springs in the wetland (Kisekka and Busingye 2015b). On another site within the study area, one community member reported: "It has been two years now that my family and the neighbouring households are enjoying the clean water. To my surprise, the well has never dried up. We attribute this constant flow of water to the earth bunds that were constructed upstream of the well to 'catch' the run-off" (Kisekka and Busingye 2015c). Scholars from Ethiopia and Taiwan made similar observations about the increase of the water table due to in situ water harvesting (Negusse et al. 2013; Liu et al. 2004).

### *3.3 Adoption Constraints*

If many farmers describe the impact of in situ water harvesting on crop yields, and a farmer without the interventions can see the results in his or her neighbours' gardens, one cannot help but ask why the interventions have not been implemented on every metre of land in Rwambu. The answer to this question could help to address some of the non-technical problems, such as: under what conditions will people take up in situ water harvesting. The research that led to this paper included a number of questions on the reasons why farmers may not to pick up in situ water harvesting. These questions pertained to knowledge and motivation.

When asked if they knew about in situ water harvesting interventions, all the farmers without interventions on their gardens responded affirmatively. They also mentioned they knew all the interventions implemented under the auspices of the project. In addition to mentioning the type of interventions, they also elaborated on the benefit of implementing the interventions. We then asked why they did not take up the interventions themselves, many farmers stated that they thought the "interventions are too tiresome to implement" (40%), followed by "I am waiting for the project …" which was mentioned 20% of the times (Fig. 7). With the last statement, the farmers meant that they waited for the project to implement the interventions on their farms. The difficulty in implementing a pilot project that aims to demonstrate technologies for which there are too few or no existing examples in the area, from which people can see the results, is that, the project starts with training

**Fig. 7** Reasons for not implementing water buffering interventions



and working with a few farmers to set up demo plots. The aim of doing this is to show what is possible, but then other people become reluctant to implement the interventions, on their gardens, without direct support from the project.

### 3.3.1 Land Availability Versus Increased Productivity

In support of the Boserup theory of agricultural transition, the next question to be asked is if land availability or increasing pressure on the land causes people to look for means to improve crop yield. Understanding the dynamics of land use, the offset market situation and the options people have for other income becomes more of a determining factor in the uptake of in situ rainwater harvesting (See also Tiffen et al. 1993).

In this context, one of the key informants reported that most of the farmers with gardens on the hill slopes implemented at least one *fanya juu* or *fanya chini* because that is the only way to secure production. Farmers on the lower slopes feel there is no need for the interventions since their gardens are not affected by soil erosion and are still productive. This partially supports the theory that people will look at improving conditions on their land only when there is increasing pressure on the land. In our study area, more in situ water harvesting interventions seem to have been implemented on the steeper slopes.

### 3.3.2 Labour Requirements

When farmers with interventions on their gardens were asked if they faced any challenges implementing or managing the interventions, 74% responded affirmatively. Two (2) challenges were mentioned: "Interventions too tiresome to implement" and "trenches easily fill with soil" (Fig. 8). These two challenges relate to the labour needed to implement and maintain the interventions.

The farmers noted that making the soil bunds and stone bunds is labour intensive, which discourages many people, but the rewards in terms of increase in crop yields make it a worthwhile investment. Seeing the results, other farmers have started to implement the water harvesting measures on their gardens, either using family labour or hiring youths or other farmers. Trenches are preferred to stone bunds because these are judged not to require a lot of effort to build by farmers.

In only a few cases, farmers adopted stone bunds themselves (so without support from the project), and the general complaint against stone bunds was that they are more tiresome to implement. This applies especially to women, who constitute the biggest labour force. Thus, 4% of farmers were found to implement stone bunds. The trenches (*fanya juu* and *fanya chini*), especially those collecting run-off from the roads and paths, got filled with sediment very fast. The *fanya chinis* on the slopes also easily filled up with sediment. So one of the constraints in the popular uptake of in situ water harvesting for stone bunds was the high initial labour investment. Interventions that require less investment such as the trenches need a lot

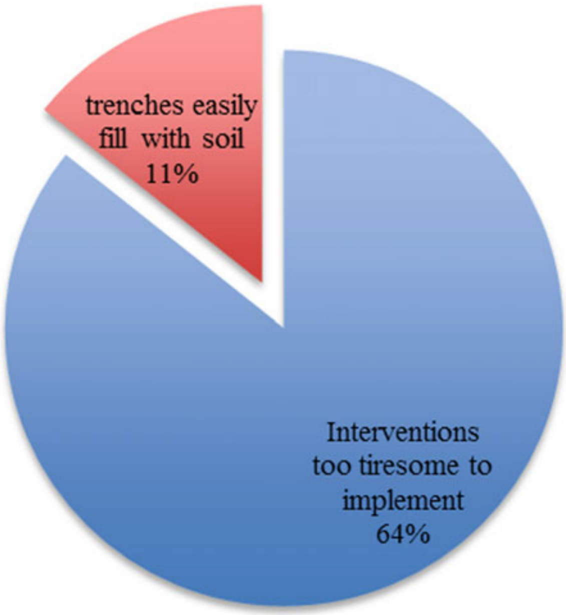



**Fig. 8** Challenges faced implementing or managing the interventions

of maintenance to remove the sediment. This discouraged people who have to rely on hired labour because they are either working elsewhere (on and off the farm) or perceive removing the sediment as a strenuous task. Indeed, it is generally known that in situ rainwater harvesting structures require considerable labour costs for their maintenance as mentioned by several authors (Bouma et al. 2016) because heavy rains may damage the structures.

### 3.3.3 Available Resources

During the interviews, it became apparent that people were more interested in trenches than stone lines. Partially, this was explained by the labour demands and partially because of the limited availability of stones. In the project area, the stones are only on the upper slopes. Also, the high demand of stones for construction (for example of schools and homes) in the villages increased the price of stones, and farmers found it more attractive to sell the stones than to use the stones to make stone lines. Selling the stones gives a quicker source of income. Because the stones are on hill slopes and many farmers live further downward, a competition over stones can be expected.

## 3.4 Testimonies of Some of the Farmers

Below, we provide six accounts of farmers who implemented in situ water harvesting measures.

### 3.4.1 Farmer One

Farmer one (male, aged 56 years) is a resident of Rwesigire village, Nyabbani subcounty, Kamwenge district. He reported how yields of beans have increased by nearly 60% on his garden after the stone bunds were implemented. In the garden where beans are grown, there are eight 15-metre stone bunds (five done by the project and three himself). In his words: "I used to plant 8 kgs of beans in quarter an acre and would harvest 40 kgs before these interventions were put in my field, but now I harvest about 100 kgs from the same piece of land yet I still plant about 8 kgs of beans". Because the fertile soil eroded uphill is quickly deposited on (and upslope of) the stone bunds, creating a somewhat level bench, farmer one has been transferring the stones from one site to another aiming to create even more fertile-level benches in his garden.

In addition to the stone bunds, farmer one has other interventions: 500 trees including *Eucalyptus grandis* and *Grevellea robusta*, five 15-metre soil bunds (four done by the project and one himself) and three 15-metre grass strips (all done by himself) (Kisekka and Busingye 2015a). The soil bunds (*fanya juus* and *fanya chinis*) were implemented in the banana plantation. Farmer one reported that the bananas growing close to the soil bunds have bigger stems and give bigger bunches, and because of that, a neighbour hired farmer one to construct three *fanya juus*, each 15 metres, on that neighbour's banana plantation (Kisekka and Busingye 2015a). While farmer one has both *fanya juu* and *fanya chini* trenches, he prefers *fanya juus* to *fanya chinis*, because the former allow water to collect upstream of the ridge and in the trench itself, allowing the water to seep slowly into the soil.

Farmer one indicated that many people are discouraged because making the bunds is labour intensive, but selling his fertile land on the lower slopes (to pay tuition for his children) left him no choice but to cultivate the land uphill and to find ways to keep it productive (Kisekka and Busingye 2015a).

### 3.4.2 Farmer Two

Farmer two (male aged 43 years) is a farmer in Rwambu IV village, Kijongo sub county, Ibanda District. He has observed a close to 50% increase on the yield of his coffee plantation. On his coffee plantation, there are nine *fanya chinis* (six done by the project and three by a group of youth he hired) of total length 600 m. In his words: "I used to harvest 6–7 bags of coffee (600–700 kgs) from my plantation (before the soil bunds were constructed), but I harvested 13 bags (13,000 kgs) last season, and I am sure to harvest even more this season".

On the same coffee plantation, farmer two intercrops bananas. He reported that the bananas close to the *fanya chinis* have bigger stems and give bigger bunches. He mentioned: "My bananas have bigger stems and yield bigger bunches—instead of the small bunches of about 5 kgs that dominated my plantation, I can now harvest bigger ones (about 15 kgs) for sale". This represents an increase of about 66% in the weight of bananas.

As reported by Kisekka and Busingye (2015a), farmer two indicated that while he hired labour to construct the *fanya chinis,* not all community members can afford that; yet, constructing the soil bunds is a laborious task. According to farmer two, the labour requirement for implementing the interventions and the inability for many community members to afford hiring labour is the main reason only a few community members have constructed soil bunds on their gardens.

### 3.4.3 Farmer Three

Farmer three (male aged 42 years), a resident of Rwemirama cell in Ibanda district, has 1.5 acres of coffee plantation. There are seven *fanya chini* trenches (all of them constructed by the project) of an average length of 15 m per trench. Each trench covers the entire width of the coffee plantation. In addition to farming coffee, he also buys the coffee from other farmers, de-pulps it and then sells it.

He reports an increase of 40–60% in the yield of the coffee on his plantation. According to his words: "I used to harvest 8–12 bags of coffee from the plantation before the trenches were implemented, but I harvested 20 bags last season, and the coffee is heavier. Previously 100 kg of dry cherries would give around 50–55 kg of coffee beans after de-pulping, but now the beans weigh around 58–60kgs".

He highlighted that constructing the interventions is labour intensive, and because of other competing uses for money, hiring labour is often not a priority. Farmer three mentioned: "For my case, I had to complete constructing the house before I can invest in anything else including making soil bunds".

### 3.4.4 Farmer Four

Farmer four (male aged 35 years), a farmer in Rwemirama cell in Ibanda district, has 1 acre of coffee. Most of the coffee trees are about 5 years old, but there are trees of 2 years planted. He has grass strips covering about one-quarter of the entire garden, in the middle slope of the garden. There are two grass strips stretching the entire width of the plantation (around 20 m) and also several short strips planted across small gulleys.

Farmer four reports an increase of around 50%. In his words: "One year ago I planted strips of lemon grass to slow running water. Running water erodes the soil and exposes the roots of the coffee, the leaves of the coffee then become yellow during the dry season. This coffee tree was almost drying, I thought it was drying because of bacterial wilt. A small gulley had formed about 1 foot from the tree, and soil had been eroded from the base of the tree. When I put the grass strips the gulley stopped deepening but instead started to fill-up with soil and litter, the leaves stopped drying and now the tree has started yielding coffee. I did not know the gulley would affect the tree that much. I used to harvest 3–4 basins of coffee from each tree per season but the previous season I harvested around 6–7 basins per tree from this section with the grass strips. The yield from the sections without grass strips did not improve much. From the younger trees I harvested 2 basins on average per tree yet the previous season I harvested 1 basin per tree. Together with the neighbours, we use some of the grass as spice for tea, but also I cut the grass and put it in the banana plantation as mulch".

Asked why he has not dug any trenches on his garden, farmer four responded that he is waiting for the project to send the trained-youth to support him and that he has asked the project's community mobiliser several times already. This testifies to the level of donor dependency created in the area, causing some people to become slow at adopting the interventions since they expect external agencies to work on their fields.

### 3.4.5 Farmer Five

Farmer five (female aged 47 years), a resident of Rwemirama cell in Ibanda district, has two *fanya chini* trenches in her banana plantation, both constructed by the project. Each trench is about 30 metres in length, collecting run-off from the road.

According to farmer five, the size of bunches has greatly improved and the bananas growing close to the trenches have bigger stems. In her words: "The plantation was not productive anymore, but now, from the bananas close to trenches, I can harvest a bunch for sell at 5000 UGX, before I could hardly get a bunch big enough to sell at, 2000 UGX". Taking the price difference as a proxy for improvement of size of the banana bunches, this would represent a 60% increment.

Farmer five mentioned the following: "The trenches get filled with sediment very fast during the rainy season. It takes 2–3 days for me to clean each trench of the sediment, I do it alone at my pace. The main constraint is the labour, especially because all children are either in school or have started their homes".

### 3.4.6 Farmer Six

Aged 29 years, farmer six is a farmer in Rwambu 4 village, Ibanda district. In his 0.75-acre coffee plantation, there are four *fanya chini* trenches (one done by the project, three jointly by him and his wife) each 25 m in length covering the width of the plantation. He reported a 66% increase in the yield of coffee on his plantation.

"I harvested 1.5 bags of coffee last season, before it was 0.5 bags. I expect around 3 bags this season".

Farmer six indicated that many people find the trenches labour intensive to implement themselves, and yet, they do not have enough money to hire labour.

## 4 Conclusions and Recommendations

This paper adds to growing evidence that in situ rainwater harvesting has the potential to increase crop yields. It showed how in the case of the Rwambu area, the entry strategies of the project play a role in the uptake and that it can be determined by past approaches of other extension agencies. Particularly, the presence of more agencies (that give free services to communities) has made people reluctant to adopt the interventions while the project is still ongoing.

The Rwambu area saw a large population increase, and for some people, this meant an increased pressure on land availability. We conclude that, confirming partially the Boserupian theory of agricultural growth, the pressure on land motivated people to implement in situ water harvesting to increase production. Their efforts pertain particularly to lands that were not yet under permanent agriculture; so particularly, when people look for new arable land, the low productivity and high erodibility start to become a key driver in uptake as people are left with less land on the lower slopes. The reduction of available land, for whatever reason, can cause rapid change in land management systems. Other external factors that influence the possible uptake include current productivity of land; if farmers consider their lands as already productive, then the added value of in situ techniques will not be seen easily. From the responses of key informants and the farmers, as well as our own observations, in situ rainwater harvesting has not only impacted on crop yields, but has also led to improved ground water levels. However, we feel there is a need to collect more data to verify and support these observations and testimonies, using controlled plots and experimental designs, where different parametres are monitored over time.

The academic discussion on the impact of in situ water harvesting revolves around the technical impact and the outcomes of longer socio-economic trajectories. The focus on the actual project procedures and actual farmers looking to increase their production at minimal expenses brings in a dimension that is less well understood. We feel it is critical to add this dimension to build up understanding of the success and failure. Unlike the government-driven interventions in Ethiopia, many developing agricultural economies depend on small-scale initiatives for the implementation of in situ water harvesting; so now that we established the positive results of in situ rainwater harvesting, we should question the distribution and uptake mechanisms.

We propose that the real push towards improving agriculture to ensure food security is in popularizing small-scale water harvesting methods and technologies adapted to the socio and biophysical environment of a place. With popularizing, we mean two activities, first, local extension agencies (government and/or non-government) need to promote best practices based on knowledge and capacities of the farmers, but also of structural aspects contributing to uptake such as pressure on land, market prices and other potential sources of income. Second, the introduction of new ideas and improvements should always be based on an assessment of the technologies that can be picked up by local communities, adapted to local conditions for maximum and long-term positive socio-economic and environmental impacts, and easily scalable by farmers. According to Cole et al. (2013), such a 'human-centred design' implies a dynamic trial and error method in which understanding the determinants of adoption is part of the learning cycle of the project.

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# Management of Rainwater Resources for Rehabilitation of Degraded Lands in Arid and Semi-arid Region of Southern Pakistan

**Sahibzada Irfanullah Khan**

**Abstract** In face of changing climate patterns and increasing livestock population, the pressure on silvopastures in dry lands of Pakistan is increasing, resulting in degradation of natural resources and loss of soil fertility. The Farm Forestry Support Project of the SDC-IC initiated rehabilitation work in 2010 in dry region of Karak using rainwater harvesting and sand dune stabilization techniques. The objective was to recover vegetation and increase land productivity. The activity was carried out jointly with farmers. Results recorded in 2015 showed a profuse plant growth in terms of trees, shrubs and grasses with a potential to provide timber, fuel wood and fodder for livestock. Conservation of moisture also resulted in growth of natural grasses and shrubs. After 5 years, plant growth in height and diameter of 6 m and 20 cm, respectively, was recorded. The vegetation cover of 45% and increase in content of soil organic matter and nitrogen were recorded. All this happened with a cost of US$82 per hectare. Rejuvenation of wells in few cases was an additional positive effect. On the other hand, annual income of US$735 per hectare from *Saccharum spontaneum* planted in sand dunes was a benefit to farmers against the other land uses in sand dunes.

**Keywords** Silvopasture · Sand dune stabilization · Soil moisture
Annual income

## 1 Introduction

Dry lands are generally defined as arid, semi-arid or dry sub-humid lands receiving less than 500-mm annual rainfall with an aridity index between 0.05 and 0.65 (the aridity index is the ratio of precipitation/precipitation evapotranspiration) (United Nations Convention to Combat Desertification 1999). There are more than 3 billion

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people globally living in dry lands that cover 40% of earth's surface (Robin 2002). Dry lands are generally defined in climatic terms as lands receiving less than 500 mm of annual rainfall. In Pakistan, the situation is severe with 75% of the country's area receiving less than 250 mm of annual rainfall (Pakistan Meteorological Department 1998). Most parts of Sindh and Balochistan and southern parts of Punjab and NWFP are falling within this dry zone (Government of Pakistan 2006).

Over 30 million people in Pakistan live in dryland areas. Their livelihoods depend heavily on the natural resource base in the form of provision of food for human beings, fodder for livestock, fuel for cooking and heating and water for drinking. Some scanty income from the sale of medicinal plants and herbs, livestock and dairy products and wildlife was also added to the meagre earnings (Fischler and Irfanullah 2006).

The poor in these ecologically fragile marginal lands are increasingly locked into patterns of natural resource degradation (Government of Pakistan 2007). There are many factors responsible for degradation of natural resources, and the climate change promotes the process by limiting the water availability and increasing temperature. Due to the low production and regeneration potential, dry lands are not able to support an ever-increasing population of human beings and livestock. Most of the silvopastoral ecosystems in dry lands are degraded due to overstocking beyond their carrying capacity, whereas rainfed croplands are increasingly being abandoned due to prolonged drought periods. These adverse factors are continuously undermining the livelihoods of poor pastoral and farming families.

## *1.1 Study Area*

The study relates to joint activities of the Farm Forestry Support Project, local NGOs and rural community organizations in Karak, one of 22 districts in the southern part of the Khyber-Pakhtunkhwa Province (NWFP) of Pakistan (Fig. 1). District Karak is situated in southern region of NWFP (Fig. 1), covering an area of 3372 $km^2$. Total population of Karak is 430,000 heads (Government of Pakistan 1998).

The area comes under tropical and subtropical climatic zone, characterized by arid and semi-arid conditions. It can be divided into three distinct geographical divisions: the dry hilly zone in north, sandy desert in south-west and sandy-loam plains in the eastern part (Irfanullah 2008). The northern hilly zone is famous for mining of various minerals like salt and gypsum. The south-western desert is characterized by shifting sand dunes, very dry and hot winds and subsistence cultivation of gram, mustard, groundnut and wheat. The eastern region is famous for a number of agricultural crops (millets, wheat and maize) and vegetables (chilies, okra, eggplant and tomato) mainly because of availability of some irrigation water. As a whole, 19% of the area is under cultivation out of which water is available for 2% of the area (Government of Pakistan 2006).


**Fig. 1** Location map of Karak. *Source* Google Earth

People in this area live on subsistence agriculture, livestock rearing and minor trade of daily use commodities. Literacy rate is surprisingly high (above 50%) as compared to the rate for Pakistan (44%) (Government of Pakistan 1998). Due to harsh living conditions and limited opportunities on land, people prefer to join civil and armed services that are mostly out of the area. The remittances they send back to their families are thus an important source of living.

## *1.2 The Dryland Ecosystems*

The interplay between human beings, land resources, climatic conditions, natural vegetation and livestock constitutes the ecosystem in most of the dry lands in Pakistan. In all these, the climatic factors and availability of water for productive practices are limiting factors. Again, in most of the cases, vast tracts of land are available, but production systems are limited to only a few patches because of climatic conditions that limit the availability of water.

In the study area, mean maximum temperature can reach to 46 °C in summer (May–September). The mean minimum temperature in winter months (November–February) goes down to 3 °C. The extreme arid conditions prevailing in major part of Karak limit agriculture to a profitless rather under-paying activity. Subsistence agriculture is totally dependent on rainfall that is sporadic, uncertain and does not exceed 350 mm per annum (Government of Khyber-Pakhtunkhwa 1998). Livestock rearing (mainly goats and sheep) is thus adopted as major source of livelihood that supports the family in terms of nutrition and income from sale of animals, wool and milk (Fig. 2).

These limitations lead towards a silvopastoral way of living where natural vegetation plays deciding role in the sustenance of the system. Sporadic grasses, shrubs and stunted trees are all what is required for grazing herds (Fig. 2). The local tree vegetation in this area includes *Acacia modesta*, *Prosopis cineraria*, *Capparis aphylla*, *Prosopis glandulosa*, *Tamarix aphylla*, *Zizyphus mauritiana*, *Olea ferruginea* and *Tecoma undulate*. Some of the important shrub species include *Zizyphus numularia*, *Vitex negandu*, *Saccharum munja*, *Callygonum polygonoides*, *Callotropis procera* and *Nannorrhops ritchiana*. Among grasses, *Chrysopogon* spp., *Cenchrus* spp. and *Cynodon dactylon* are important, whereas *Salsola foetida*, *Withania* spp. and *Erva javanica* are common herbs. The natural forest is limited to only 2% of the total area on distant hills (Government of Pakistan 1998), comprising mainly *Acacia modesta* and *Olea ferruginea*.

Availability of water for drinking purpose is also not certain. The water table is as low as 500 ft., and it costs high to drill and pump the water out. There were some natural springs in the hills that were providing drinking water to communities but dried out in recent droughts (1992, 1998 and 2002).

**Fig. 2** The dry lands in Karak, Pakistan. *Photograph* Irfanullah Sahibzada

### *1.3 Statement of the Problem*

Most of the people in Karak live below poverty line. Their livelihood is dependent on rainfed subsistence agriculture and livestock. The livestock is then dependent on natural range vegetation in the form of low trees, shrubs and grasses. However, due to increasing drought conditions and scarcity of rainfall, the agriculture is not more a productive activity and croplands are increasingly abandoned. To fill this gap in livelihood, the number of livestock per household is increasing with time. This exerts great pressure on natural vegetation of the rangeland area that gets grazed more intensively and more frequently. This leads to the degradation of ecosystem and depletion of natural vegetation. The scanty rainfall condition, hot weather and sustained grazing pressure restrict recovery potential of natural vegetation. The phenomenon thus adds to desertification that compounds the problem of poverty and makes communities utterly vulnerable to the situation.

The net effect of the problems stated above is observed in the form of increase in poverty and vulnerability of the poor. The droughts leave negative effects on their capacity to survive. In the efforts to survive, they become heavily indebted, their health is badly affected, and most of them migrate to urban areas.

## 2 Methodology

Keeping in view the importance of natural vegetation and the support it does provide to local livelihoods, the Farm Forestry Support Project (FFSP) funded by Swiss Agency for Development and Cooperation (SDC) and executed by Intercooperation-Pakistan, started the dryland management and rehabilitation programme in District Karak. The purpose was to rejuvenate the productive capacity of degraded lands so that the support these lands were providing to livelihoods previously could be restored (Shah 2011).

Based on the detailed area surveys and consultation sessions conducted in the region by experts from FFSP through the local NGOs and farmers' communities, rehabilitation measures were designed to address the problem. In order to regain the depleted vegetation cover and thereby restore the soil fertility for increased production in silvopastoral lands, the "Hillside Ditch" technique was specifically designed and applied on 5 sites within the district. The technique aimed at taking maximum advantage of atmospheric water (rainfall) for increased biomass production for human and livestock needs (Farm Forestry Support Programme 2015).

## 2.1 Design Parameters

The hillside ditches were designed for these silvopastoral lands with gentle sloping topography (below 30°) to enable the use of machinery (tractors) for reducing labour cost (Fig. 3).

Continuous ditches along the contour line having plant pits at regular interval were excavated (Fig. 3). The ditches were 66 cm wide and 30 cm deep, with excavated soil from ditch placed on downhill side making continuous ridge of 30 cm. The soil excavated from plant pits was placed within the ditch on one side of plant pit to impound water. Spacing of ditches and plant pits was kept as 7 and 5 m, respectively (Fig. 4). The size of the ditches and spacing of plants and ditches were fixed keeping in view the rainfall of the area.

The plant pits were planted with tree species that were fast growing and having fodder value. The interspaces between plants were sown with seeds of grasses and fodder shrubs to have maximum utilization of space. The species used on different sites included *Acacia albida*, *Dalbergia sissoo*, *Acacia nilotica*, *Melia azadarich* and *Acacia Victoria* in trees; *Dodoneae viscose* and *Acacia modesta* in shrubs; and *Sorgham almum* and *Cenchrus ciliaris* in grasses.

On sites with sand dunes that kept shifting with winds, a sand dune stabilization technique with a local species called "Khana" (*Saccharum spontaneum*) was applied. *Kana* suckers were obtained from an adjacent district at the cost of Rs. 7 per sucker and planted at a spacing of 5 m × 3 m in straight lines (Fig. 10).

## 2.2 Instruments

The hillside ditches were excavated with the help of a tractor-driven "Ditcher" specially designed for the purpose to reduce cost. The ditcher that was fabricated in a local workshop consisted of a modified form of mouldboard plough commonly used by farmers in hilly areas for cultivating hard gravelly soils. The front two

**Fig. 3** Layout site of hillside ditches *Photograph* Irfanullah Sahibzada

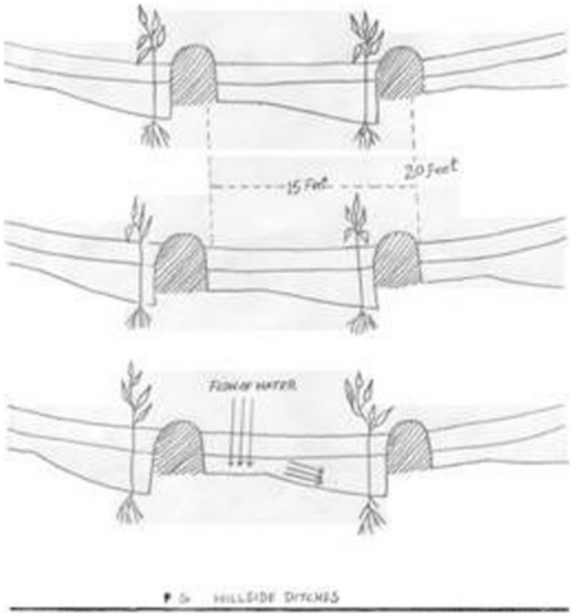


**Fig. 4** Design of hillside ditches

**Fig. 5** Ditcher, specialized instrument for ditch making. *Photograph* Irfanullah Sahibzada

blades were replaced with strong chisels and the rear blades by enlarging its length to 1 m and depth to 0.6 m (Fig. 5).

For reducing the cost of manually excavated plant pits within the ditches, a pit excavator was designed and used (Fig. 6). The front blade commonly used with tractor was modified to have a top width of 1 m and bottom width of 0.6 m.

The pit excavator was fitted with the tractor in front to excavate pits in hillside ditches. The pit excavator was so used that it produced a gently increasing slope towards the planting point from the middle of the space between two plant pits.


**Fig. 6** Pit maker for making pits in ditches. *Photograph* Irfanullah Sahibzada

### 2.3 Operational Details

Function of the whole arrangement of ditches and pitting was to take maximum benefits of rainwater in arid zones by making maximum rainwater available for plant growth for prolonged period. This was with the purpose to eliminate high establishment costs in arid zones involving labour in plantation and manual watering at frequent intervals. By keeping the depths of ditch, the ridge and pits within the ditch as 30 cm each, a 90 cm deep and 66 cm wide space at each planting site was made available for storing run-off water coming from up-slope side. By keeping the space between ditches and plant pits as 7 m and 5 m, respectively, rainwater falling on 35 $m^2$ land surface on uphill space was collected at each planting point.

## 3 Results

### 3.1 Physical Evidences

The maximum on-site conservation of rainwater and its utilization for plant growth was the major effect visible on these sites. In an area arid to a limit that could not support the slow-growing vegetation produced fast-growing trees and obtained profuse growth of shrubs and grasses within a few years of time (Fig. 7).

According to the data collected from different sites, the average survival rate of trees planted was 40%, the average number of trees growing per hectare becoming 218. This number was manifold more than the number of trees growing on these types of lands without treatment (i.e. 14 trees per hectare) (Pakistan Forest Institute 2005). The height and diameter growth rate on these sites recorded was also considerably higher. Maximum diameter and height growths were recorded in case of *Acacia albida* as 20 cm and 6 m, respectively, followed by *Acacia nilotica* as 15 cm and 5 m, respectively (Figs. 8 and 9; Table 1).

**Fig. 7** Growth of grasses after one year. *Photograph* Irfanullah Sahibzada

**Fig. 8** 6-year-old trees of *A. nilotica. Photograph* Irfanullah Sahibzada

Due to retention of run-off and percolation of run-off water into soil on the site, a profuse growth of local annual and perennial grasses was recorded, in addition to the *Sorgham almum* and *Cenchrus ciliaris* that were sown during plantation activity. The average soil cover on these soils recorded was 45%, considerably high over normal cover on these degraded lands (10–15% on the average). These grasses and shrubs were of high value as a feed for local goats and sheep. The farmers were advised not to allow animals for grazing in initial 2 years. They could, however, cut grasses and stall-feed their animals during these 2 years.

**Fig. 9** 3-year plants of *A. nilotica. Photograph* Irfanullah Sahibzada

**Table 1** Growth data for trees, shrubs and grasses in hillside ditches

| S. no. | Parameter | Species | Data recorded |
|---|---|---|---|
| 1 | Average diameter | *Acacia albida* | 20 cm |
| | | *Acacia nilotica* | 15 cm |
| 2 | Average height | *Acacia albida* | 6 m |
| | | *Acacia nilotica* | 5 m |
| 3 | Av. no. of trees surviving/hectare | Overall | 218 numbers |
| 4 | Average vegetation soil cover | Overall | 45% |

*Source* Survey data

The activity also contributed to the overall fertility status of soil. The laboratory analysis of soil samples taken at three sites each from treated and controlled plots showed a higher organic matter content and total nitrogen concentration in treated plots. A slight increase in phosphorus content and decrease in lime content could also be attributed to the treatment of site. No significant change in the electrical conductivity, pH and potassium content was however recorded. The treatment period of 5–6 years was too less to demonstrate any significant change in soil properties, except the content of organic matter that was recorded higher in treated plots (Table 2).

In addition to increase in on-site productivity and soil fertility, the activity also contributed to the recharge of groundwater in down the slope areas. According to information provided by local community, two wells that dried out due to prolonged drought were rejuvenated near to the activity sites.

On the other hand, the Khana belts served the purpose of windbreaks for sandy croplands and contributed to household income in the form of proceeds from sale of its stalks and leaves. The *Saccharum* plant was found most suitable for sandy land as it did withstand against prolonged droughts, lesser cost involved in its establishment and high return for its marketable products (Fig. 10).

**Table 2** Soil properties in treated and controlled plots

| No. | Parameters | Control plot | Treated plot |
|---|---|---|---|
| 1. | Organic matter (%) | 0.65 | 1.01 |
| 2. | Total nitrogen (%) | 0.13 | 0.20 |
| 3. | Phosphorus (mg/kg) | 3.05 | 3.14 |
| 4. | Potassium (mg/kg) | 155.13 | 114.1 |
| 5. | Electrical conductivity (dS/m) | 0.10 | 0.13 |
| 6. | Lime content (%) | 6.96 | 6.75 |
| 7. | pH (1:5) | 8.29 | 8.38 |

*Source* Khattak (2015)

**Fig. 10** *S. spontaneum* in sand dunes. *Photograph* Irfanullah Sahibzada

## *3.2 Cost Analysis*

Due to use of specialized instruments and machinery, the cost was very low for applying hillside ditch technique to the development of silvopastures. The total cost including use of machinery, planting stock, seeds and labour was calculated as US $82 per hectare (Table 3).

It is important to mention that the extra cost involved in this activity was that of using specialized techniques. This, however, drastically reduced the cost of manual watering as implied in ordinary plantation activities by the Forest Department or other agencies. The usual cost per hectare plantation activity by the Forest Department was Rs. 19,800 or US$330 (as per exchange rate of Rs. 60/USD in 2009) that was considerably higher than the cost on using hillside ditches (Government of Khyber-Pakhtunkhwa 2003; FATA 2015). The additional benefit of this silvopasture development was that it re-established the whole vegetation cover as compared to ordinary plantation work that considered only trees.

**Table 3** Cost analysis of silvopasture development per 1 ha of land

| Activity | Cost description | Rate (Rs.) | Amount (Rs.) | Amount (US $) |
|---|---|---|---|---|
| Preparation of hillside ditches with tractor and ditcher | 3 h | 300 | 900 | Total cost = US$82 @ PK Rs. 60/ $ (2009) |
| Preparation of pits with tractor and pit blade | 2.5 h | 300 | 750 | |
| Planting stock | 540 Plants | 2/plnt | 1080 | |
| Planting with first watering | 540 Plants | 2/plnt | 1080 | |
| Restocking (30%), including cost of plants and planting | 160 Plants | 4/plnt | 640 | |
| Grass seed | 3 kg | 50/kg | 150 | |
| Seed of shrubs | 2 kg | 100 | 200 | |
| Sowing of shrubs' and grasses' seeds | 1 Labour day | 100 | 100 | |
| Total cost (Rs.) | | | 4900 | |

*Source* Sahibzada (2015)

**Table 4** Annual cost/benefit per hectare for various crops of sand dunes in Karak

| Cost/Benefit | Kanola (Rs.) | Gram (Rs.) | Mustard (Rs.) | *Kana* (Rs.) |
|---|---|---|---|---|
| Annual cost | 6052 | 9139 | 10,003 | – |
| Annual income | 14,795 | 53,097 | 74,055 | 44,100 |
| Net Profit (Rs.) | 8743 | 43,958 | 64,052 | 44,100 |
| Net profit (US$) (@ of Rs. 60/USD of 2009) | USD 146 | USD 732 | USD 1067 | USD 735 |

*Source* Agriculture Research Station Karak (2015)

In case of sand dunes, total cost per hectare of *Kana* establishment including the cost of suckers and labour was Rs. 5000 (US$83). The average annual return from *Kana* site was Rs. 44,100 (US$735) that was profitably comparable with other land uses available for sand dunes, except wheat (Table 4).

The investment cost for *Kana* was only one time as this was a perennial plant. It was cut each year and sprouted again (Fig. 11). Both the long stalks and leaves were sold in market (these were used for furniture making, as roofing material, sunscreens and making of decoration items). The outstanding characteristic of *Kana* was that its production did not depend on rainfall and even did well in prolonged droughts when all other crops failed.

**Fig. 11** Harvesting of *S. spontaneum. Photograph* Irfanullah Sahibzada

## 4 Discussion

The study faced all those constraints common in dealing with a common resource in social environment. It could have produced better results if the land resource use patterns were in control of the study team. However, it is a fact that more than 60% land in Karak is treated as wasteland where free and unrestricted herding and grazing of animals is practised. Due to no or lesser productivity of economic goods, the use rights for livestock grazing are not reserved. Free, unrestricted and extensive grazing of animals is thus practiced by local communities, even by those who do not own any land and totally depend on their livestock.

The rehabilitation measures however demand care of the land and protection from grazing for initial two years to provide relief to the recovering vegetation. Due to silvopastoral practices that have become a way of life, it is difficult for landowners to abandon grazing on their land. It is due to this reason that communities usually demand for fencing the area or keeping watchmen to protect the site which enormously increase the establishment cost of the activity.

Without attending to the protection parameters, activity in some places has resulted in no conspicuous results after the planted seedlings and shrubs were completely clean washed by roaming herds of goats and sheep.

On the other hand, it is a common concept among local people that investing on silvopastures is a profitless venture. Failures due to water shortage in past and the lack of protection from free grazing animals have further strengthened this perception. The already marginalized communities therefore find it very difficult to invest on pasture development.

To overcome these constraints, the project used a vigorous campaign to convince the local resource users (herders and farmers) for restricting their herding practices to untreated lands. The project team ensured in return to limit the treatments to a small portion (1/4th) of the grazing lands to provide sufficient grazing fields for the herds. At the same time, a concept of social fencing was used where farmers' associations in the target communities and adjacent villages were taken into confidence for the activity and they were then able to control the unattended grazing practices.

Whereas this paper addresses the problem faced by a wider population of herdsmen and farmers dependent upon farming and livestock resources in a pattern that is common to the dry southern landscapes of Pakistan, India and many other adjacent countries, the land use pattern in dry parts of many these countries may vary and the coping strategies for all those lands will vary accordingly for producing similar results. This study is therefore limited in scope keeping in view the resource use patterns.

The study produced visible effects in terms of revamping the biomass reserves of the area. However, the more desired effect on soil fertility and its organic content was not visible or verifiable in the limited span of this study. For measurable effects in these parameters, a longer period monitoring is required.

## 5 Conclusions

The interventions in silvopasture development and sand dune stabilization have proved significant in overcoming the water shortage and rejuvenating the vegetation for the benefit of human beings and livestock. The cost of these activities is also very low and within the bearing capacity of farmers. Every effort has been made to make use of local instruments and material like the improvised “ditcher” and “pitter” which were the modified forms of already in-use agricultural implements. The study in the given socio-economic and geophysical environment produced results that could be of use and interest to many scientists and practitioners working in similar environment and dealing with similar problems. Particularly, the subtropical dry lands in many neighbouring countries can be a suitable ground for tackling these problems with these or adjusted techniques.

However, a strategy needs to be worked out beforehand to control the constraints elaborated in the previous section to eliminate or minimize the effects of free grazing. These facts and results need to be spread wide through extension and mobilization of communities at regional level. The mater of free livestock grazing should be managed at regional and not at local level. Communities should be facilitated to reach a mutual consensus for protecting sites under treatment and keeping their animals grazing in other areas. A controlled grazing system in which area is divided into blocks, keeping one block under protection on rotational basis, may also be one of the options.

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The commitment and efforts of local NGOs (*Khwendo Kor* and *Yaraan* in Karak) who were involved in contacting the communities, selection of sites and discussing all the matters with community organizations at grass-roots level are highly appreciable. These organizations and their role are crucially important in the sustainability of the activity on long-term basis.

Technical expertise and support provided by Dr. Bashir Hussain Shah (the FFSP Consultant) in the initial phases of the activity was very much helpful in designing tailor-made interventions for sites in the field. Dr. Shah's knowledge and experience is enlightening many minds in many organizations in many parts of the country because of his dedication to the development.

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# Rainwater Management to Restore Ecosystems and Foster Food Production: A Case Study in the Semiarid Region of Minas Gerais in Brazil

**Norma Angélica Hernández-Bernal**

**Abstract** Rainfed agriculture is vital for the subsistence of the population in the semiarid region of the Minas Gerais state in Brazil. However, annual rainfall is concentrated into four months and varies from 250 to 800 mm while evaporation rate is high all through the year. This region is one of the poorest regions in Brazil and lack of water and soil management has resulted in the degradation of local ecosystems, in low yields from crop production, and in increasing social and environmental vulnerability. This study aimed to evaluate the efficiency of micro-rainwater harvesting (MRWH) techniques (Negarim, Semicircular bunds, Contour bunds, and Contour ridges) in enhancing water infiltration in the soil profile and in improving soil structure and crop production. Trees were used as bioindicators to test the techniques' effectiveness in storing water in the soil profile to enhance plant growth. Monthly measures of soil stability, superficial infiltration rate and humidity percentage in the soil profile were made for one year. The results showed that the RWH techniques were effective in retaining soil humidity, improving soil characteristics and enhancing plant development, even during the dry period.

**Keywords** Micro-rainwater harvesting · Soil structure · Restoration
Food security

## 1 Introduction

Crop production in semiarid regions depends on rainfed systems; climate variability makes them vulnerable to environmental and social stress. Water is a critical and key resource for reaching sustainable development in the long term and local rainfall constitutes the main source of water in arid and semiarid regions.

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Eighty percent of agricultural in the Brazilian semiarid region is rainfed (Rockström et al. 2003; UCC-Water 2005).

The region is highly populated and the need for food has created great pressure on natural resources by opening new areas for agriculture and cattle raising. Silva et al. (2004) found that 20% of the Brazilian semiarid region has lost its original vegetation to agriculture and cattle raising. This has altered the endemic vegetation structures—*Caatinga* and *Cerrado* biomes—losing biodiversity, accelerating erosion processes and affecting water quality, all of which reflect in the social and economic development of the population in the region (Klink 1996).

This paper presents a proposal to use micro-rainwater (MRWH) harvesting techniques as a tool to restore soil field capacity, improve crop production, and to minimize climate vulnerability. The introduction presents the importance of rainfed agriculture in semiarid regions and the importance of the water–soil nexus for food production and environmental and social stability. Throughout history, rainwater harvesting has played an important role in providing access to water for basic human needs in different countries. The semiarid region of Minas Gerais presents specific geographic characteristics and distinct agricultural and grazing practices. These are key points to understand the causes and the consequences of environmental degradation and how rainwater harvesting can help to restore the soil and improve subsistence agriculture at the local level. The proposed methodology uses previously applied methods in the restoration of grasslands in other semiarid areas. The results demonstrate the performance of each one of the systems tested and are followed by a discussion highlighting the existing importance of rainwater inclusion within the scope of water management in areas facing environmental, socioeconomic vulnerability, and climate uncertainty.

### 1.1 Environmental Integrity, Food Security, and Social Stability

Evidence from archaeological sites shows that agriculture constitutes an indicator of the close relationship between environmental degradation and the economic decline of some ancient civilizations. In Mesopotamia, with an excessive use of water and elevated evaporation rate, soils were affected by salinization which undermined their fertility. In Mesoamerica, the Mayans had to supply food to a fast-growing population; this led to the expansion of their agriculture areas and to the thin rainforest productive but fragile soil to erode at faster rates. In both cases, environmental degradation and soil exhaustion diminished water availability that caused food scarcity and along with it, politic and social conflicts (Brown 1997; Toscano and Huchim 2004).

This evidence is present nowadays. China, India, and USA, among other countries are losing an important amount of fertile soils and their capacity for cattle herding and food production is diminishing (Brown 2001, 2009; Pimentel and

Buruess 2013). Furthermore, climate change will induce water stress as well as drought and desertification processes, mainly in tropical and subtropical regions where poverty and hunger concentrate today. Extreme climate events will modify the projections of agricultural supplies in the medium and long terms and these must also be considered to assure food and water security (Rockström et al. 2009; UNEP 2009; Gleik 2014; Jiménez Cisneros et al. 2014).

Within this context, the role played by rainfed agriculture is quite important, especially for subsistence farmers. The study of rainwater harvesting techniques at the local level must focus on the fact that they are effective tools for food security due to their efficiency in securing water during dry spells.

## *1.2 Environmental Resilience Through Rainwater Harvesting*

In semiarid regions, available water is over-exploited and there are problems of degradation of other environmental components like loss of vegetation, soil, and biodiversity (Brown 1997; Vörösmarty et al. 2005; Rodríguez–Estrella 2014).

Seasonal rains are the source of freshwater supplies in tropical and subtropical regions but rain runs off too quickly to be used in an efficient way. Developing countries in these areas use approximately only 20% of their potentially available water resources (Hinrichsen and Tacio 2002). Rainwater harvesting can be used to increase water availability for both human or animal use and agriculture.

Rainwater harvesting can be defined as the process of concentrating, gathering, and storing rainwater using a surface where runoff can occur, for agricultural or domestic use. In some places—the American Continent, Middle East and Asia—archaeological evidence exists that these systems were used for domestic purposes hundreds of years B.C. (Evenari et al. 1982; Toscano and Huchim 2004).

According to the classification established by Critchley and Siegert (FAO 1991), Siegert et al. (FAO 2003) and Ngigi (2003), when the collected runoff water is directly applied to the cropped area during the rainfall event, the system does not use long-term storage. The soil profile serves as a water reservoir and the method of irrigation is called *runoff farming*. Two scales can be applied: macro-catchment and micro-catchment water harvesting. The first one is characterized by a large catchment area (greater than 1000 $m^2$) outside the arable area and is mainly implemented to produce annual crops. The second one is characterized by a relatively small catchment area adjacent to the cropping one and is used for the growth of a single tree, fodder shrubs, or annual crops.

These techniques have proved to be effective in augmenting food production in semiarid and temperate regions around the world (Dijk 1997; CONAF-JICA 1998; Ojasvi et al. 1999; Castillo and Gomez-Plaza 2001; Li and Gao 2003; Kudakwashe et al. 2004).

The use of runoff farming techniques to reforest degraded areas has promoted environmental restoration in some semiarid regions. Studies and research to restore degraded areas have been performed in the semiarid province of Gansu, in China, in Karnataka, in India, and in the semiarid region of Chile (CONAF-JICA 1998; Sanmuganathan et al. 2000; Droppelmann and Berliner 2003; Goel and Kumar 2005; Li et al. 2005, 2006).

Within this context, the aim of this study was to use MRWH in the semiarid region of Minas Gerais, in Brazil as a tool to increase humidity in the soil profile and biomass accumulation to favor soil–plant interaction that could lead to a rapid restoration process and increase the options of water and land use/management. The parameters and results presented here are related to humidity retention in soil profile and to superficial soil stability in the site.

The MRWH techniques tested (Fig. 1)—(a) Negarim, (b) Semicircular bunds, (c) Contour bunds, and (d) Contour Ridges—have reported their effectiveness to increase crop production in arid and semiarid regions where other kind of irrigation systems can result quite expensive. In addition, these techniques allow the use of a small catchment area with an infiltration pit, ease infiltration, and retain enough humidity in the radicular zone for the development of the plant (FAO 1991; Renner and Frasier 1995; Kahindaa et al. 2008; UNEP 2009; Oweis and Hachum 2004; Ali et al. 2010; Yosef and Asmamaw 2015).

As defined by Critchley and Siegert (FAO 1991), Prinz and Malik (2002), Siegert et al. (2003) and Ngigi (2003), the four structures are classified as runoff farming techniques: Negarim are diamond-shaped basins surrounded by small earth bunds with an infiltration pit in the lowest corner of each one of the micro-basins. The Semicircular bunds are earth embankments in the shape of a semicircle with the tips of the bunds on the contour line. Contour bunds follow the contour, at close spacing, and by construction of earth ties, the system is divided into individual micro-catchments. Finally, Contour ridges follow the contour at a spacing of 1–2 m and runoff is collected from the uncultivated strip between ridges and stored in a furrow just above the ridges. Bushes or young trees are usually planted in the infiltration pit. Both, the plant and the infiltration pit help to reduce superficial runoff, diminish erosion and facilitate water penetration in the soil profile.

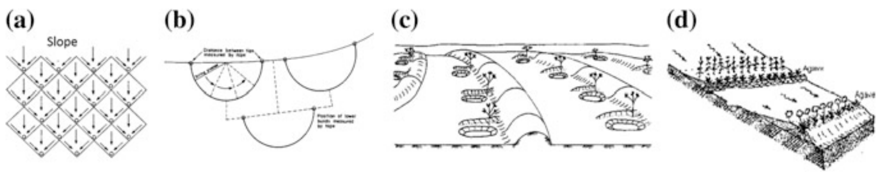



**Fig. 1** Runoff farming systems tested. *Source* a, b, and c: Critchley et al. (1991). d: Siegert et al. (2003). Reproduced with permission

# 2 Methodology

## *2.1 Study Area*

A study performed by the Brazilian Environment Ministry and the Federal University of Pernambuco stated that more than 20 million hectares—22%—of the Brazilian tropical semiarid region are affected by environmental degradation (Fig. 2). The north and north-eastern parts of the state of Minas Gerais are included in this semiarid region (Sá et al. 2003; Silva et al. 2004).

The north and north-eastern part of the state of Minas Gerais is a densely populated area and has one of the lowest Human Development Indexes in the country. In this region, farmers have stripped big areas of its original vegetation to grow crops, but mainly to grow grass for cattle grazing.

These practices have eroded and compacted the soils and there has been an overexploitation of the available superficial and underground water (Silva et al. 2004). Besides degrading the environmental resources, these practices are restraining the possibility of economic and social development.

The site of this study is located within the Itinga municipality in the middle part of the Jequitinhonha Valley (Fig. 3) in the Teixeira river basin, between 16° 25′ and 16° 52′ lat. S, and 40° 45′ and 40° 16′ long. W (Fig. 4). It has an average annual precipitation of 700 mm (lowest values are around 300 mm), concentrated in 3–4 months, with a mean annual temperature of 24 °C, and with an elevated evaporation rate all year long.

The configuration of the Teixeira river drainage pattern has been altered, as well as its soils and vegetation, accelerating the speed of erosion, soil compaction and loss of original vegetation, leading to modifications in the local runoff arrangement.

## *2.2 Methods*

The methodology proposed for this study is a collection of different methods to measure a set of parameters applied in grasslands in semiarid regions. This is the first time the methodology proposed here, adapted to the study area, has been applied for the environmental restoration of a semiarid region in Brazil.

### 2.2.1 Micro-rainwater Harvesting Systems

The geomorphologic and soil characteristics of the site, as well as the average annual precipitation, were considered in the selection of the four runoff farming techniques (FAO 1991; Prinz and Malik 2002; FAO 2003). Social, cultural, and economic aspects of the population in the study site were also taken into account—the four systems present the advantage of being low-cost, hand-build earth

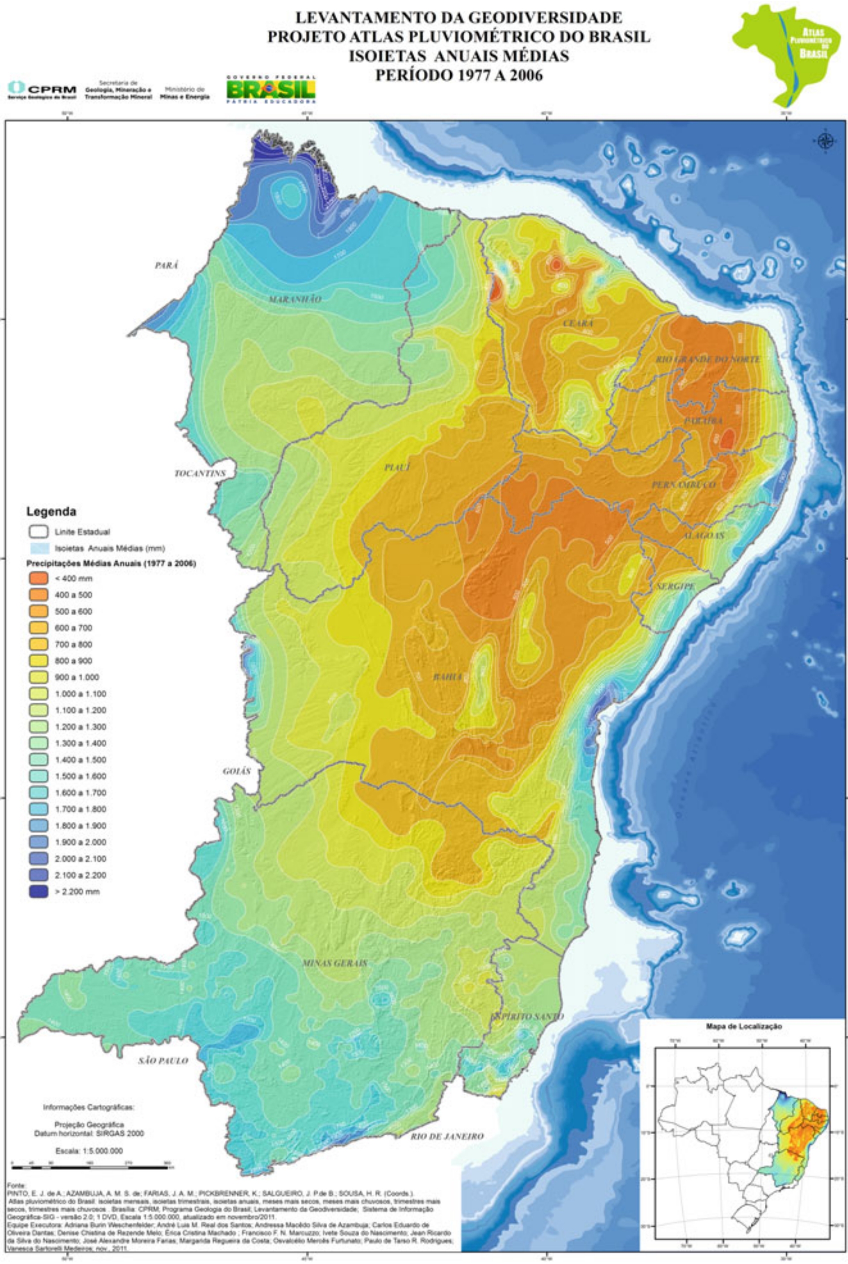



**Fig. 2** Brazilian semiarid region and its average annual rain (1997–2006). *Source* Pinto, EJ et al. (2011)

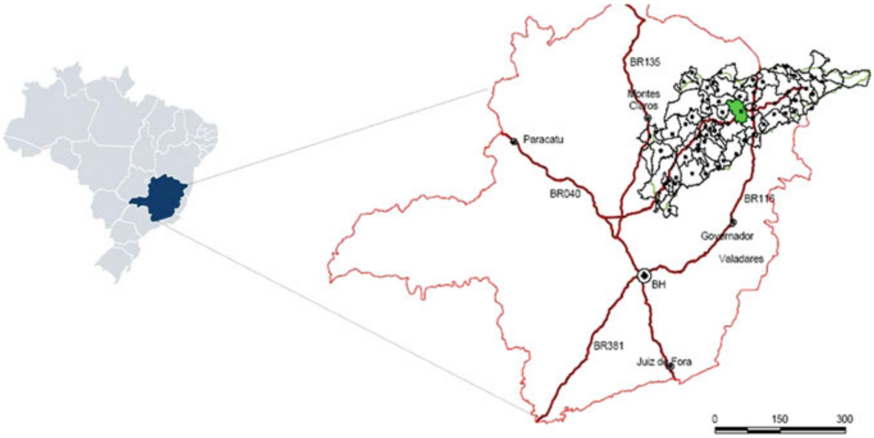
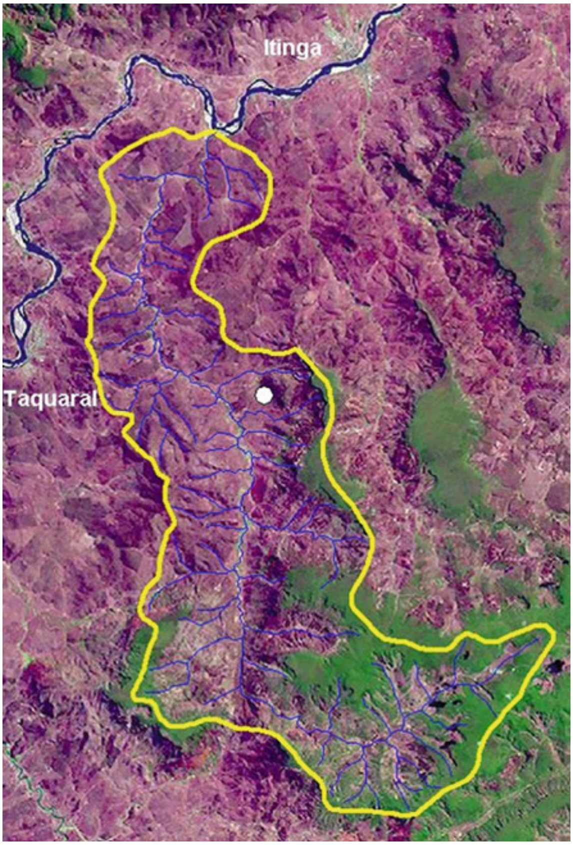



**Fig. 3** Localization of Itinga municipality within the Jequitinhonha Valley

**Fig. 4** Study site in the Texeira river basin



structures, easy to implement, to replicate, and to be adapted (FAO 1991; Renner and Frasier 1995; Kahindaa et al. 2008; UNEP 2009; Oweis and Hachum 2004; Yosef and Asmamaw 2015).

The MRWH structures were built following the contour line, with 3-m spacing contour interval. A 25 cm deep, 30 cm wide furrow and an infiltration pit were excavated and the extracted material was used to form 30 cm high bounds with a 75 cm wide base, to delimit each micro-basin. Depending on the runoff farming system, the space between each micro-catchment area was defined from 3 to 4.2 m. The infiltration pit had a depth of 40–50 cm, following the recommendations by Critchley and Siegert (FAO 1991) and Siegert et al. (FAO 2003).

To evaluate the runoff farming systems in this study, two experimental plots were set, due to the homogeneity of soil composition. Both areas—Experimental Area 1 (EA1) and Experimental Area 2 (EA2)—were located in unproductive areas which had been abandoned for eight and four years, respectively. EA1 was heavily compacted (Fig. 5), while EA2 had been covered with bushes and invasive vegetation (Fig. 6). The plots were located on 5–7% slopes with deep lateritic soils (Oxisols). The four runoff farming systems were implemented on each plot with an area of 200 $m^2$ for each system ($S_1$ = Negarim; $S_2$ = Semicircular Bunds; $S_3$ = Contour Bunds; $S_4$ = Contour Ridges) and a 200 $m^2$ Control Area. Rain was the only source of water, so there was no supplementary watering at any time of the study.

Up to 160 trees were planted and to be used as bioindicators to obtain two indicators of tree development—number of leaves and height for each tree. Photographs were taken to register qualitative changes in the site and the development of the trees (Hernández-Bernal 2007).

### 2.2.2 Superficial and Subsurface Soil Structure

Superficial and subsurface soil structure parameter defines the degree of soil structural development, erosion resistance and reflects soil biotic integrity, because the organic matter that binds soil particles together must constantly be renewed by plant roots and soil organisms (Herrick et al. 2005). Sampling and measuring the superficial and subsurface soil aggregate stability were performed following the

**Fig. 5** Experimental Area 1 (EA1) before the implementation of the RWH structures. *Photograph* Norma Angélica Hernández-Bernal

**Fig. 6** Experimental Area 2 (EA2) before the implementation of the RWH structures. *Photograph* Norma Angélica Hernández-Bernal

methodology proposed by Herrick et al. (2005). A number to classify the soil stability was given for each sample according to Table 1.

As reported by Herrick et al. (2005), sites with values over five (5) are highly resistant to erosion particularly if there are few areas with no vegetation. High values also reflect a good hydrologic function since stable soils are less prone to disperse or clog soils pores during rainstorms. Statistical analysis was made using ANOVA, to compare the average value for each system. Monthly registers were performed from December 2005 to January 2007 (Fig. 7).

### 2.2.3 Soil Moisture

Soil moisture was measured in C = Control; $S_1$ = Negarim; $S_2$ = Semicircles; $S_3$ = Contour Bunds; $S_4$ = Contour Ridges at two different soil profile depths: 20 cm and 40 cm, taking into account that within this depth range there is root

**Table 1** Criteria for assignment to stability class

| Stability class | Criteria for assignment to stability class |
|---|---|
| 1 | 50% of structural integrity lost (melts) within 5 s of immersion in water or soil too unstable to sample (drains through sieve) |
| 2 | 50% of structural integrity lost (melts) 5–30 s after immersion |
| 3 | 50% of structural integrity lost (melts) 30–300 s after immersion or <10% of soil remains on the sieve after five dipping cycles |
| 4 | 10–25% of soil remains on the sieve after five dipping cycles |
| 5 | 25–75% of soil remains on the sieve after five dipping cycles |
| 6 | 75–100% of soil remains on the sieve after five dipping cycles |

*Source* Herrick et al. (2005)

**Fig. 7** Sample fragments of superficial (left) and subsurface soil (right). *Photograph* Norma Angélica Hernández-Bernal

development. These measurements were registered using *Soilmoisture5201F1G-Blocks* (Soil moisture Equipment Corp.) (Fig. 8). Soil moisture data was measured from June 2006—in the middle of the dry season—to January 2007—rainy season—and was recorded weekly. Data obtained for this indicator did not present a normal distribution so the statistical analysis was performed with the Friedman nonparametric test.

# 3 Results

## 3.1 Superficial and Subsurface Soil Structure

Through the data recorded, changes were observed in the soil conditions. EA1 had an improvement of the soil aggregates in all the systems and was particularly

**Fig. 8** Soil moisture monitoring. *Photograph* Norma Angélica Hernández-Bernal

evident in the subsurface samples. Biologic activity increased and favored the integration of soil particles in the soil and, due to high temperatures, leaf litter decomposed providing nutrients to the soil. Due to the change in soil structure and the content of organic matter, some areas, which originally had no vegetation, started to grow grass and weeds benefitting from the available soil moisture in the superficial profile layers in the EA1.

Figure 9 shows the changes of the soil stability average values all throughout the monitoring period in EA1. Observation revealed that initially all systems had similar values for superficial soil. System S4 reached a Stability Class value 4 showing a better performance than the rest of the systems and even significantly more if compared to the values of the Control Area. In relation to subsurface soil, the presence of trees, the action of roots, and the incorporation of organic matter by biologic organisms contributed to the improvement of soil stability. While the Control Area samples remained unchanged, systems $S_1$, $S_2$, $S_3$, and $S_4$ showed positive changes. Systems $S_1$, $S_2$, $S_3$ kept a similar average value along the period, while $S_4$ improved soil stability conditions more rapidly by the end of the rainy season—March 2006—and remained high even during the dry season (Fig. 9).

In EA2, all soil samples had a good level of stability, due to a bigger amount of organic matter in its content as well showing less compaction. The initial samples, both superficial and subsurface soils, already had an average qualification of 3–4 indicating soil resistance to erosion processes (Fig. 10).

Soil stability parameter is strongly related to plant development and to the production of vegetation that is transformed into organic matter and is incorporated into the superficial horizon of the soil profile. Humidity, vegetation, temperature, and other elements, such as biologic activity, promote the decomposition and incorporation of organic matter which aggregate soil particles and enhance superficial infiltration and air circulation between the particles, improving field capacity.

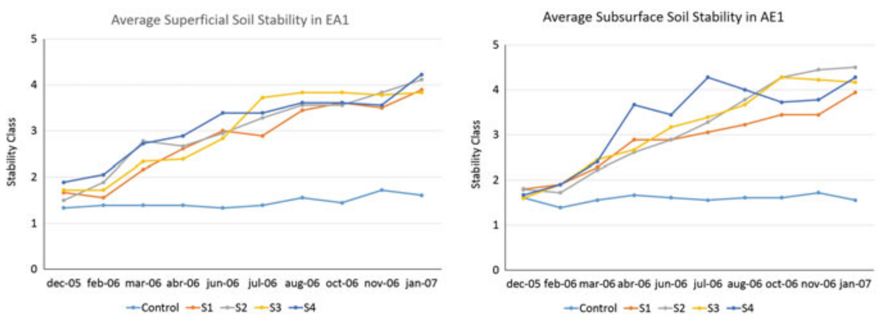



**Fig. 9** Average soil stability for superficial and subsurface soil in EA1

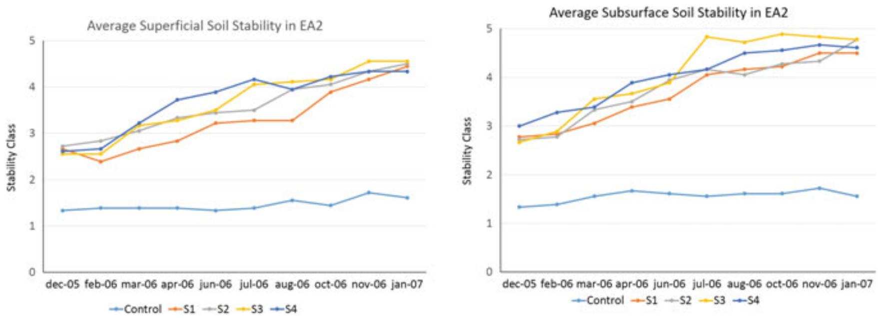



**Fig. 10** Average soil stability for superficial and subsurface soil in EA2

## 3.2 *Soil Moisture*

The first rains following the construction of the rainwater harvesting structures showed that water infiltration in the pits and furrows allowed the vegetation to grow and stabilized the earth bunds (Fig. 11).

Along the study period, data showed that soil moisture improved in both areas, showing a positive evolution for each treatment. On EA1, $S_1$, $S_2$, and $S_3$ presented similar median values as the Control Area at 20 cm depth, which was enough moisture for the tree to survive just before reaching the wilting point. Treatment $S_4$ showed a better performance on storing and maintaining enough soil moisture for the water needs of the plant (Fig. 12). The values obtained at 40 cm depth, were similar for $S_1$, $S_2$, and $S_3$, but presented higher values if compared with the ones obtained for the Control Area, which showed a significant difference in the median, meaning a poor performance on soil moisture retention. Treatment $S_4$ had a better performance allowing water to infiltrate and to retain soil moisture, avoiding the mulching point of the plants (Fig. 12).

**Fig. 11** Vegetation growing over the earth bunds and stabilizing the RWH structures in EA1 after the second rain event. *Photograph* Norma Angélica Hernández-Bernal

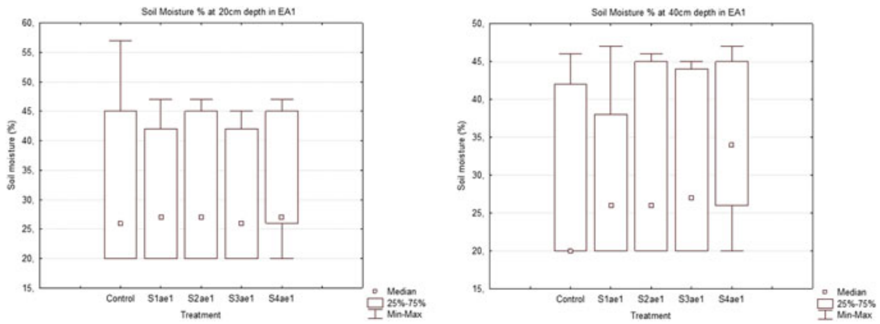



**Fig. 12** Soil moisture content in EA1 for 20 and 40 cm depths

Values of soil moisture content in EA2 were different due to previous soil conditions. However, $S_4$ had a better performance on storing water all through the experiment. This positive change can be related to better drainage conditions in the soil profile, since this plot area was neither exposed to erosion nor to compaction and was covered with secondary vegetation before the experiment. The median values were quite similar for the Control Area, $S_1$ and $S_3$ at 20 cm depth, while $S_4$ showed a better performance in general for the same depth, as all values for this last system were concentrated among 27 and 45% (Fig. 13). The values obtained at 40 cm depth reflected a similar behavior among the Control Area and treatments $S_1$, $S_2$, and $S_3$. Treatment $S_4$ was more efficient to keep soil moisture in the soil profile during the dry season (Fig. 13).

The survival rate of trees by the end of the monitoring period in EA1 was of 47% while in EA2 was of 98%. This results showed that lack of water and soil compaction limit vegetal production even more than lack of fertility, which can be overcome with the incorporation of manure and other soil management measures to favor plant development. Table 2 indicates the efficiency of the parameters considered in the study for each of the runoff farming systems tested.

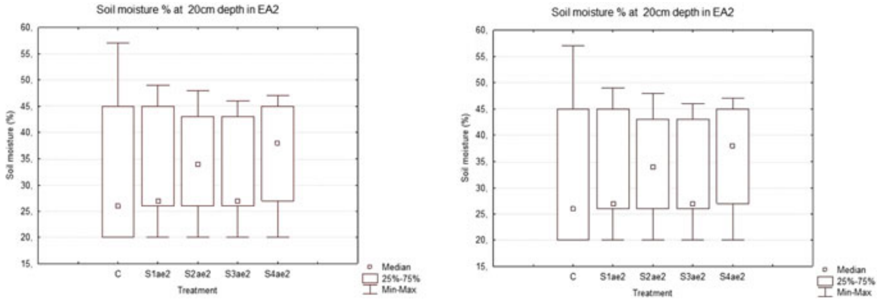



**Fig. 13** Soil moisture content in EA2 for 20 and 40 cm depths

**Table 2** Efficiency of the tested runoff farming systems

| Indicator / System | $S_1$ | $S_2$ | $S_3$ | $S_4$ |
|---|---|---|---|---|
| Plant development 1. Height | red | yellow | green | green |
| Plant development 2. Canopy (number of leaves) | red | green | green | green |
| Soil humidity | yellow | yellow | yellow | green |
| Soil Aggregate Stability | yellow (orange) | yellow (orange) | green | green |
| Infiltration rate | red | red | green | green |
| Tree survival rate | red | yellow | red | yellow |
| Building and maintenance costs | red | red | yellow | green |

| | |
|---|---|
| Low efficiency | red |
| Efficient | yellow |
| High efficiency | green |

## 4 Discussion

Management of rainwater harvesting used in combination with other soil conservation techniques can contribute to diminishing the effects of dry spells in the semiarid region of Minas Gerais and even lessen the effects of climate change. Research on other semiarid regions has demonstrated that the increment of soil moisture, high temperatures and the concentration of organic matter and litter under the bushes or trees allow nitrogen retention and stimulate biological activity increasing the fertility of the soil (Cross and Schlesinger 1999; Bunch 2012). Caravaca et al. (2002) found out that the physical condition of the soil aggregates improved due to the presence of different micro and macro-organisms, which was observed in both Experimental Areas during the period of the study, even during the dry season.

The rainwater harvesting techniques tested can have a long-term impact in the production of plants, either for reforestation or in agricultural activities, allowing the smallholder farmer to integrate an agro-ecological approach and benefit their socioeconomic situation. Assessment of soil restoration using these techniques along with the incorporation of other soil conservation measures such as zero tillage, mulching or the use of organic manure could help solve fertility problems (Unger et al. 1991; Caravaca et al. 2002; Bunch 2012). However, the common regional practice is to allow the agricultural area to “rest” for several years in order to recover its fertility even though frequently no recovering occurs. Most of the time, the green residues that could be incorporated into the soil are used to feed the livestock. However, it is necessary to keep track of the changes in soil stability, an indicator of erosion, and monitoring the changes in the soil structure will help to avoid fertility loss and secure crop production (Herrick et al. 2005). Monitoring the different parameters will allow to keep control of the changes, however, the methodology used still must be tested, improved and applied in similar sites.

The success or failure of rainwater harvesting systems in the region is directly related to climate variability, the irregular rainfall patterns, and the soil texture and composition. The low capacity of infiltration in the Control Area indicates that the soil in the study area has a poor structure. As mentioned above, the decomposition of organic matter and litter enhances infiltration and moisture retention in the soil profile. The RWH structures were constructed manually on slopes that varied between 5 and 7% to generate local runoff during rainfall. The runoff was conveyed by each micro-basin to the furrows and pit holes over the contour curve, either with an intermittent earth bound ($S_1$ and $S_2$) or continuous ridge ($S_3$ and $S_4$). These structures promoted the infiltration process and reduced the erosion during storms.

This experience demonstrated that the implementation of rainwater harvesting structures allowed a better rate of infiltration, increased the moisture available for plants by almost 20 percentage points and contributed to the adequate development of the planted trees, as well as the growth of herbaceous and invasive vegetation, demonstrating the potential for these structures to ensure food security and confront the uncertainty of climate change.

However, institutional assessment of smallholder farmers must be performed to demonstrate the potential of rainwater harvesting as an efficient tool in agriculture, not only productive use of water but also for environmental and soil conservation measures.

As stated by Falkenmark and Rockström (2004) and Wani et al. (2009), policies must have a socio-environmental perspective, recognizing rainfall as a freshwater resource that should be managed along with superficial and underground water. Water management policies should recognize the importance of rainwater harvesting systems to reduce runoff losses and for rain water storage, either in surface reservoirs or by infiltration into the soil profile (UNEP 2001; Woyessa et al 2006; UNEP 2009; Wani et al. 2009). The adoption of rainwater harvesting techniques as a tool for food production and environmental restoration should be accompanied by institutional research to be applied at different scales to improve rainwater use efficiency and to deal with the uncertainty of climate variability (Wani et al. 2003; Water Aid 2008).

Although starting at the smallholder level, the aim should be to apply rainwater harvesting management and policies to the regional watershed scale, from household supply and crop production to aquifer recharge (Ngigi 2003; Sivanappan 2006; Water Aid 2008).

## 5 Conclusions

Despite the past two decades of working on restoring riparian ecosystems and headwaters in watersheds through afforestation, Brazil has done little research on the application of water harvesting techniques to restore degraded environments.

This paper shows that the use of these micro-rainwater harvesting techniques can attenuate the effects of dry spells, contribute to the management of soil fertility and increase soil moisture for crop production at the small and local scale.

This study demonstrated the importance of rainwater management to restore degraded natural resources as well as to face climate variability and reduce the possibility of crop loss. These low-cost structures allow the efficient use of water harvesting in arid and semiarid regions for food production and can help to restore self-sufficiency in rural systems with less pressure on the environment. Rainwater management needs to be supported by better governmental policies that start at the smallholder level by letting local people manage local resources and adapting their agriculture practices to face the possibility of extreme climate variability. In parallel, the results and knowledge must be transmitted through capacity building activities at the smallholder level and up to the watershed level.

By focusing on the existing links between environmental integrity, food security, and social and economic development, the possible imbalance of these elements leading to social or environmental catastrophe can be avoided. In the case of a severe drought, this vulnerable region could face the outbreak of severe social conflicts for water and food. Through the implementation of varying scales of rainwater harvesting structures supported by local agriculture institutions and water management policies, explosive social conflict can be avoided.

Even though geographic conditions in this semiarid region are not favorable to sustainable crop production or livestock activities, these limitations could be partially overcome by the effective management of natural resources in accordance with their natural potential of resilience, and thereby diminishing the economic pressure on natural resources.

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# Lessons Learned in the Replication and Scaling-up of Rainwater Harvesting Technologies in Arid and Semi-arid Areas: A Case Study of Kilifi County, Kenya

**Charles Kipkorir Songok, Paul Kimeu, James Kamunge, Raphael Ngumbi, Lotome Chammah, Christine Adiema and Christine Omondi**

**Abstract** In the arid and semi-arid lands in Kenya, agricultural water scarcity, which is characterized by high rainfall variability, is the most significant determinant of livelihood risks and food insecurity. Despite rainwater harvesting holding significant potential for sustaining dryland production systems, its adoption and replicability are still low. This paper analyses the lessons learnt in promoting the adoption and replication of rainwater harvesting technologies and small-scale irrigation in the arid and semi-arid lands in Kenya. The findings demonstrate that rainwater harvesting technologies have a huge potential in promoting climate resilience and food security. This paper shows that, in order to optimize the production potential of rainwater technologies, policy makers should integrate biophysical and socioeconomic conditions in the design and implementation. The potential to adopt, replicate and scale-up can further be catalysed using participatory technology development and dissemination approach. This approach can provide a platform to combine better land management and good agronomic practices that can enhance the production potential of rainwater harvesting technologies.

**Keywords** Adoption · Small-scale irrigation · Participatory technology
Land management · Agronomic practices

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## 1 Introduction

Rainfed agriculture plays an important role in sustaining the livelihoods of communities in the arid and semi-arid lands (ASALs) of sub-Saharan Africa. In Kenya, in particular, climate change and variability are the key determinants of low and unstable production (Dercon 2002) and are the dominant sources of household income and consumption risks (Zimmermann and Carter 2003). Due to high rainfall variability and recurrent droughts, subsistence households in the ASALs often suffer the consequences of climate-induced shocks (Salami et al. 2010), mainly in terms of food insecurity. This is because of the limited capacity to investing new adaptive technologies and practices (Thompson et al. 2007; Thorlakson and Neufeldt 2012)

According to the IPCC (2008), climate-related hazards will exacerbate other stressors, with negative outcomes on rainfall dependant livelihoods, especially for the poor. In the ASALs, changing rainfall regimes are altering hydrological systems and affecting rangeland resources in terms of quantity and quality. Climate change is projected to reduce crop yields and intensifying competition for declining natural resources, with consequences on food security (Challinor et al. 2007; Maina et al. 2013).

In Kenya's ASALs, rural communities depend on natural resources to sustain their livelihoods. However, most of them are persistently haunted by famine and food insecurity because of unreliable rainfall patterns (Mwadalu and Mwangi 2013). These communities possess limited capacity to invest in technologies that can enable them to harness rainwater for productive purposes. With increasing land and water management challenges, there is need for adoption of innovations that increase the efficient use of rainwater (Rockström et al. 2009; Funk 2010).

According to Lebel et al. (2015), food security in the ASALs is extremely susceptible to erratic rainfall patterns. While climate change could lead to an increased frequency of dry spell events and shortened growing seasons, improved soil and water management strategies such as rainwater harvesting (RWH) can effectively increase the resilience of cropping systems. By decreasing the intensity and duration of intra-seasonal dry spells, RWH reduces significantly the risk of a failed season and stabilizes crop yields. Therefore, RWH technologies have the potential to become a key adaptation strategy to climate change by bringing an increasingly valuable contribution to food security in the ASALs through securing crop farmer livelihoods (Malesu et al. 2007; Kimani et al. 2015).

Observations by the World Bank show that the plethora of the literature on work done to increase agricultural productivity in the last 25 years have failed to achieve widespread, spontaneous adoption of promising techniques on a larger scale. This is because when farmers are presented with a technique that reduces production risks and increases returns; they adopt it (World Bank 2010). An example in the ASALs is the insecurity of land tenure which greatly reduces farmer's willingness to invest in physical works to improve water availability, and even to adopt agronomic practices (such as mulching or zero tillage) that would enhance production.

Over the past two decades, the World Food Programme (WFP) has been supporting the Government of Kenya (GoK) in providing humanitarian relief to food insecure communities in the ASALs. However, since 2009, WFP, jointly with GoK, ASAL county governments and non-state actors, has been implementing cash assistance for assets (CFA) projects in ASALs. CFA is a food security intervention whose goal is to build the resilience of poor communities to perennial food security shocks. The communities adopt RWH technologies that enable them to produce and diversify food and income sources, making them food self-sufficient (Bezuayehu et al. 2009). In turn, WFP provides a cash transfer, which covers half of the value of the total household food basket (Diang'a and Ngigi 2009; WFP and GoK 2013).

The CFA projects are geared towards six outcome areas: (i) improved access to water for human use and livestock production, (ii) increased pasture and fodder production for livestock, (iii) improved crop production and diversification of food and income sources, (iv) reduced environmental degradation, (v) improved access to the markets and (vi) build the capacity of communities to plan, implement and manage food security projects.

This paper, therefore, analyses the experiences and lessons learnt in the replication and scaling-up RWH in the ASALs. The paper highlights the factors affecting adoption, replication and scaling-up of RWH technologies. The findings, though specific to Kilifi County, provide useful lessons that can catalyse the diffusion rate of RWH technologies in the wider ASAL context.

## 2 Methodology

### *2.1 Study Area*

Kilifi County is located in the coastal region of Kenya, bordering Mombasa and Kwale to the south, Taita-Taveta to the west, Tana River to the north and north-east (Fig. 1). The county lies between latitude $2^0$ 20′ and $4^0$ 0′ South, and between longitude $39^0$ 05′ and $40^0$ 14′ East. The county covers an area of 12,610 $km^2$ and has a population of 1,246,228 (KNBS 2009).

The county has various physiographic and topographic features. The coastal plain varies in width from 3 to 20 km (KoR 2013). The marine swamps are endowed with mangrove forests and marine sediments that support marine culture. The Nyika Plateau lies to the west and occupies about two-thirds of the county. This area is mainly an ASAL zone. It is sparsely populated and is covered by thin vegetation, shallow depressions and gently undulating terrain. The plateau is drained by seasonal rivers, which form Sabaki River that empties into the Indian Ocean. The main livelihood systems in this zone include subsistence farming. Livelihoods in the ASAL area are heavily dependent on rainfall and are frequently affected by droughts or floods. CFA projects are concentrated in this area.

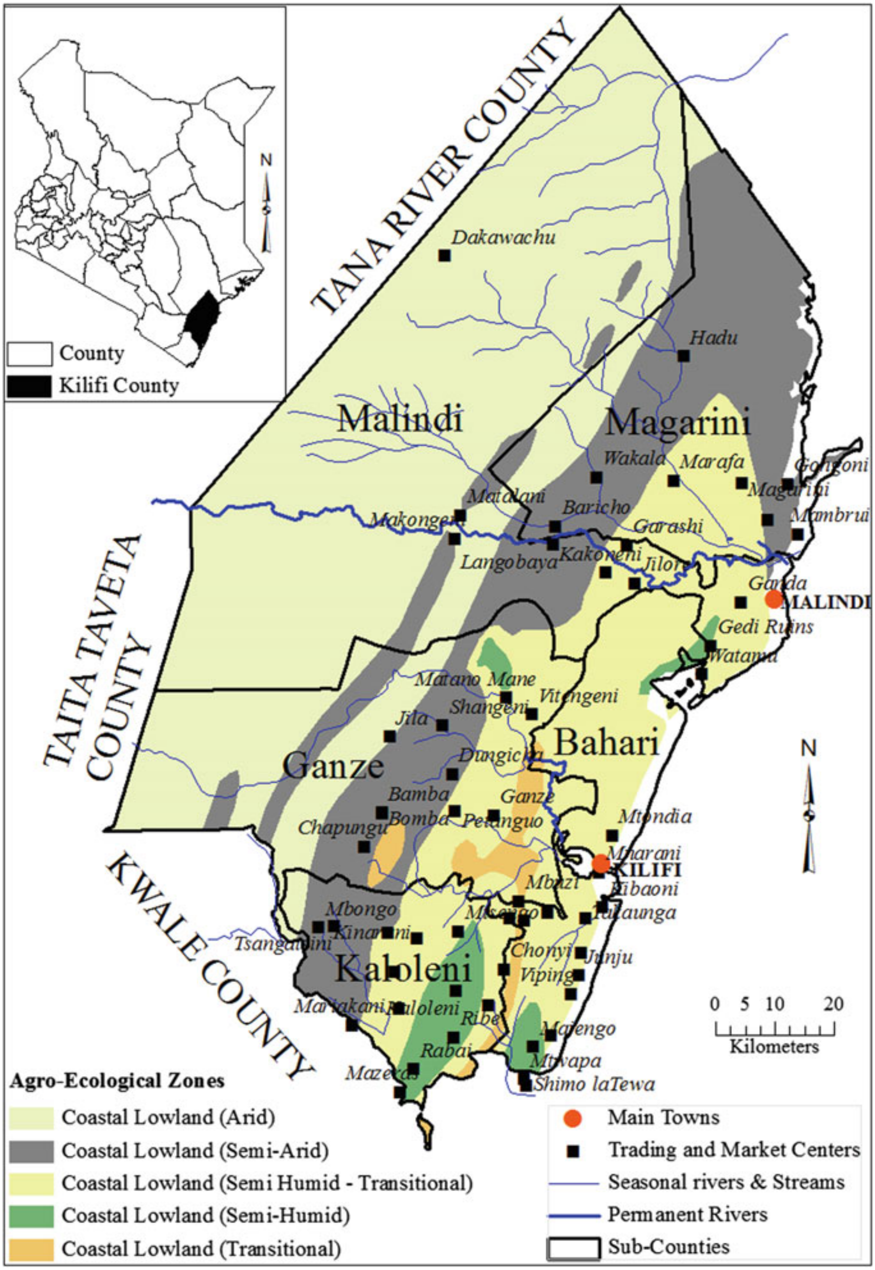


**Fig. 1** Map of ASAL areas and Kilifi County in Kenya. *Source* KoR (2013)

The average annual rainfall ranges from 400 mm in the hinterland to 1200 mm at the coastal belt (Jaetzold and Schmidt 2009). The coastal belt receives an average annual rainfall of about 900−1100 mm with marked decrease in intensity to the north and to the hinterland. The county receives two main rainfall seasons in a year: long rains (April to June) and short rains (October to December). In the hinterland where rainfall is very unreliable, variations between seasons are barely noticeable. Rainfall patterns in the hinterland are influenced by proximity to the Indian Ocean, relatively low altitudes, temperatures and winds. Mean annual temperatures in the hinterland range between 30 and 34 °C. Rainfall distribution influences livelihoods. The southern coastal belt supports seasonal crop farming, while the hinterland is suitable for livestock and game ranching.

## 2.2 Methods

This paper summarizes the experiences gained and lessons learnt from implementing CFA projects in the ASALs in Kenya in the past six years. The findings have been synthesized from a combination of: (a) desk review of periodic monitoring and evaluation reports, (b) field visits and key informant interviews with targeted and non-targeted households as well as unstructured interviews with and key informants and (c) review of relevant literature on resilience building and food security interventions. The discussions presented in the following sections will be based on field experiences in implementing RWH and irrigation technologies in Kilifi County (Table 1), although these findings are relevant to the arid areas.

The RWH technologies discussed in this case study encompass all practices of rainwater collection, storage and efficient utilization for crop production and are classified into three categories (Biazin et al. 2012) (Fig. 2):

a) Micro-catchment RWH systems: collection of surface runoff from micro-catchment systems with water storage in the soil for dry spell mitigation,
b) Macro-catchment RWH systems: collection of surface runoff from macro-catchment systems with water storage for supplementary irrigation,
c) In situ RWH systems: techniques for maximizing infiltration, reducing surface runoff and soil evaporation and improving soil and water availability.

**Table 1** Targeted households and RWH technologies

| County | Households | Main RWH and irrigation technologies |
|---|---|---|
| Kilifi | 9833 | Zai pits, water pans, terraces, sunken beds, negarims, farm ponds, small-scale irrigation systems |

*Source* WFP (2013), GoK (2013)

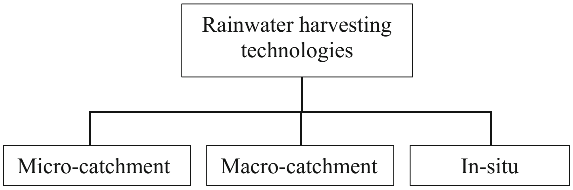


**Fig. 2** Classification of RWH systems for food security

# 3 Experiences and Lessons Learnt in Implementing Resilience Building Interventions

## *3.1 Limitations in the Design of the CFA Projects*

The RWH technologies and small-scale irrigation system offer huge potential in building livelihood resilience because of its ability to improve production and diversify livelihood options under water stress conditions (Ngigi et al. 2011). In addition, these technologies support asset accumulation and by exploiting the advantages offer by group dynamics, they improve social and human capital. This approach, according to Béné et al. (2012), is instrumental in building the adaptive capacity of vulnerable populations.

The weakness to sufficiently attune beneficiaries (who were accustomed to humanitarian relief) to the new thinking around livelihood resilience building and reducing dependency on external assistance continues to slacken the potential to replicate and scale-up RWH technologies (Ngigi et al. 2011) in most of the ASAL areas where CFA projects are implemented. Field experiences depict the perception that some targeted beneficiaries engage in CFA activities with the intention of receiving a cash or food transfer, rather than to build their resilience to future shocks. This narrows the long-term vision for building livelihood resilience.

In addition, the challenges associated with unpredictable funding sources, sometimes, cause delays in the disbursement of the cash transfers. This was noted by Ngigi et al. (2011) to demotivate beneficiaries, hence making them not to effectively participate in CFA projects. Considering that resilience building, at scale, needs sufficient resources, unpredictable funding will continue to slacken the pace of replicating and scaling-up RWH technologies, making it risky to effectively achieve the expected outcomes of CFA projects.

## *3.2 Replication and Transferability Potential of RWH Technologies*

Even though early adopters demonstrate higher replication of RWH technologies in their farms, responses from key informants highlight a number of inhibitors. These include: the labour-intensive nature of CFA projects, costs associated with installation, operation and maintenance of especially water efficient drip irrigation systems that utilize water buffered using farm ponds for the production of high value crops, wavering commitment of beneficiaries due to delays in cash transfers and lack of a participatory extension system to accelerate the diffusion rate of these technologies and practices (Ngigi et al. 2011).

Analysis of records from periodic monitoring reports indicates that over the past six years, households that have adopted and replicated RWH technologies observed improved yields. As shown in Table 2, the data collected in a baseline exercise in 2013 shows a substantial increase in legume yields, before and after implementation of CFA projects. The average increase in yields was attributed by respondents to the ability of RWH technologies to harness sufficient moisture in the soil that was able to sustain the legume crops to maturity. This has greatly reduced crop losses or failure due to water stress at critical stages of the crop. There is potential to achieve higher yields, but this is curtailed by poor agronomic practices, inefficient use of irrigation water and lack of extension support.

Despite the potential that RWH technologies hold for food production, its adoption is still sub-optimal, though varied, among communities. Some of the key factors that have been highlighted by Boithi et al. (2014) include low literacy levels among household decision-makers and inadequate access to technical and financial support. In addition, social (gender and land tenure issues), ecological (local biodiversity, water harvesting potential and soil erosion), economic (poverty and willingness to invest in new technologies) and climate (seasonal rainfall variations) are some factors that influence the adoption of RWH technologies.

In areas where "high-tech highcost technologies" have been implemented, such as small-scale irrigation systems, replication dismal. This is due to the relatively high investment costs and inability for most farmers to access finances. However, in areas where low-tech low-cost RWH technologies have been implemented, especially to grow high-value crops, this has freed small-scale farmers from rainfall dependence, thus allowing farmers to grow crops year-round. In these cases, replication households is high. This is because RWH technologies are affordable, and replication can easily be aided by communities working together in groups on a rotational basis from one farm to another.

A preferred approach, however, is a mix of low-, medium- and high-tech technologies, because it balances the contrasting challenges of technology selection, cost, social acceptance, adoption, adaptation and diffusion. It is not enough for an innovation to be technically sound; it must also be adaptable to suit specific local conditions, affordable and preferred among subsistence communities to achieve

**Table 2** Average yield of selected crops in semi-arid counties

| County | Main crops | Average yield (90 kg bags per acre) | | |
|---|---|---|---|---|
| | | Before CFA | After CFA | % change |
| Kilifi | Maize | 2.9 | 5.1 | 76 |
| | Cow peas | 2.9 | 6.7 | 131 |
| | Green grams | 1.5 | 3.4 | 127 |

wider diffusion (WFP and GoK 2013). It is evident that adapting the RWH technologies to local agro-climatic and ecological contexts is not the only key to optimizing the production potential of these technologies. Selection of appropriate technologies enhances the functionality and efficiency in harnessing rainwater within limitations of the local climatic and landscape conditions.

In the semi-arid lands of Kenya, land tenure is a major inhibitor to production and a source of conflicts because of the communal nature of land ownership, which limits access and the ability to invest in the land. De Trincheria et al. (2016) state that farmers are naturally more willing to adopt and replicate technologies that provide significant and sustained returns in terms of increased food production and farm income. However, farmers who have insecure land tenure, limited access to inputs, water rights and market information are less likely to invest time and money in RWHM technologies (Medhin and Teklehaimanot 2013; Bouma et al. 2016).

## *3.3 Potential of RWH Technologies in Enhancing Household Food Security Shocks*

This section describes two case studies that demonstrate the potential for RWH irrigation management in enhancing food security at the household level.

**Case 1: Increasing production and income through adopting RWH and irrigation**

Dangarani community CFA project was started in 2009 by 233 households (HH) in Mitangani location, Ganze Sub-County, Kilifi County in Kenya. Their aim was to build livelihood resilience to persistent food security shocks. Erratic rainfall, persistent droughts and prolonged dry spells affected the main livelihoods (livestock keeping and marginal agriculture) in the area. Using participatory rural appraisal (PRA) techniques, the community identified water scarcity as the main problem affecting their livelihood. The group set up a demonstration farm in every village, where they constructed zai pit plots to rehabilitate the degraded land, conserve soil moisture and restore soil fertility to support food production. Zai pits guaranteed the community a harvest, even in poor rainy seasons.

Building on this success, households have replicated zai pits. In 2012, the community excavated a water pan, with a capacity of 10,000 m$^3$. This has enabled them to reduce the distance to water sources from 7 to 10 km to less than 1 km. The water pan provides water to Mitangani secondary school which has a population of more than 635 students. The need to optimize opportunities for livelihood diversification prompted the community to construct sunken beds for growing vegetable to meet household food needs and income. Sunken beds, like zai pits, were selected due to their suitability for the terrain and soils, ease in water application (flood irrigation) and ability of the berms to retain soil moisture.

In 2014, the community opened up 3 acres (1.22 ha) under drip irrigation. Using treadle pumps, water from the pan was pumped into elevated water storage tanks and channelled to the crop fields via gravity. Using drip irrigation has greatly improved water use efficiency. The community works in groups, each cultivating 1 acre fitted with complete drip kits. In the first cycle, the community planted egg-plant, tomatoes and kales which were sold to Mitangani secondary school, earning about USD 100 weekly (Fig. 3).

This case study demonstrates how RWH technologies can enable subsistence farmers to surmount the challenges of drought. Through the linkages with extension services, they have overcome the production challenges associated with poor agronomic practices (use of fertilizer, weed management), limited knowledge on agribusiness and market linkage, poor record keeping on production. To reduce the cost of production, the community have adopted composting as a source of manure, to replace inorganic fertilizers, and as an agribusiness venture, where they generate additional income from the sale of mature manure. Additionally, the group engages a private sector player, Equatorial Kenya Limited, which promotes the production of the African Birds Eye (ABE) chillies. Through contract farming, the farmers are able to overcome the bottlenecks linked to market access.

## 3.4 Technical Support and Capacity Development

A review of monitoring reports shows that the sub-optimal benefits from the use of RWH technologies could be due to inadequate technical support. In some instances, poor siting of technologies limits its effectiveness in harnessing rainwater. An example is the siting of irrigation projects in flood-prone areas without provision of dykes to control floods. Moreover, inability by farmers to conform to technical design and implementation considerations affect the functionality and efficiency of the technologies, hence reducing its production potential.

In some projects sites, the resulting imperfections in the replication of RWH technologies are linked to limitations in information dissemination, inadequate access to field extension and technology-fit. For example, in some project sites in Kilifi County, despite adopting RWH technologies, most households continue to

**Fig. 3** Community members attending to kale crop in their farm. *Photograph* Charles Songok

apply poor agronomic practices in their production systems. A baseline reconstruction and outcome monitoring study conducted in 2013 showed that the average yield per zai pit among sampled households ranged from 0.5 to 1.5 kg. This compares poorly with the recommended 2–3 kg per zai pit, translating to less than 50% of the production potential that zai pits hold (WFP and GoK 2013). The reasons for these include poor use of uncertified seeds, poor timing of planting, occassioned by late land preparation which results in late sowing of seeds, high plant densities in standard 2 $ft^2$ zai pits, poor soil fertility management and inadequate access to extension services.

It is common in project sites where design considerations have been overlooked for structures to be exposed to potential risks. Good examples include water pans that break the embankments due to poor workmanship (mainly arising from lack of designs and limited supervision), unfenced and unlined farm ponds that present security risks and accelerate water loss through seepage, respectively. In addition, poor application of good agronomic practices like cover cropping and mulching to reduce excessive moisture loss, intercropping or crop rotation, crop diversification and poor soil fertility management point to the limitations in optimizing the production potential of RWH technologies. These factors, partly contribute to the limited replication potential of RWH technologies.

## *3.5 Weak Community Institutions and Project Management Capacities*

Establishment of effective community institutions is the key in ensuring project sustainability. In irrigation systems, successful operation and maintenance (O&M) requires strong community institutions that are able to ensure optimal performance of irrigation systems. In addition, management and organization (M&O) is critical in the effective and efficient use of RWH technologies. Strong community institutions are important in catalysing the replication of technologies at the community level.

Despite CFA projects identified through a community-based project planning process, the combination of weak community institutions and the limited ability to cultivate a shared thematic focus and community vision threatens the sustainability of CFA projects. Review of periodic monitoring and evaluation reports deduces some lessons (WFP and GoK 2013). First, there is need for considerable sensitization of the frontline extension agents, on the purpose of CFA projects in building livelihood resilience. Second, capacity building activities are ideally integral to participation, yet they have not been adequately used as avenues for transferring skills and knowledge on O&M and maintenance and organization (M&O). Third, participation of beneficiaries is a consequence of how benefits from the technologies are shared.

### 3.6 *Insecurity and Land Conflicts*

Resource-based conflicts and political interests affect project implementation and full achievement of the outcomes from RWH technologies. One of the initial reasons for political interference was the opposition CFA activities by local leaders due to labour-intensive needs and in adequate sensitization on the transition from humanitarian relief to CFA (Ngigi et al. 2011). Potentially disrupting conflicts that arise within communities inhibit adoption of technologies.

In areas that are predominated by pastoral livelihood systems, frequent conflicts over access to and control of agricultural fields, which are in most cases, sited adjacent to grazing fields, is a common source of resource use conflict. Moreover, during the water stress seasons, most irrigation systems perform below capacity due to increased competition for water resources between livestock herders and farmers on one hand and the declining river levels on the other. Moreover, irrigation schemes that depend on water from rivers are often the hotspots of conflict between upstream and downstream water users, sometimes resulting in abandonment of projects (Ngigi et al. 2011). The loss of investments in these irrigation schemes, has a bearing on the sustainability of such projects.

Moreover, in most project sites bordering wildlife conservation areas or near wildlife migratory routes, seasonal conflicts between farmers and wildlife are common. Wildlife usually destroys crops and tramples on RWH technologies. In most cases, when conflicts arise, beneficiaries either migrate or abandon the farms where they have established the RWH technologies. This is one of the major challenges to the sustainability of CFA projects, particularly among communities residing adjacent to wildlife parks. As water challenges continue, conflicts are expected to persist, hence the need to strengthen community management institutions to reduce potential triggers of conflict. In addition, stronger partnerships with the national and county governments, as well as agencies responsible for wildlife management are key.

## 4 Discussion

The RWH technologies highlighted in this paper have a huge impact in promoting climate resilience and food security. Although the experiences make reference to Kilifi County, the results are replicable to ASAL areas in general due to their similarities in rainfall variability and unreliability. Although climate change is recognized to have negative consequences on food security and livelihoods, subsistence farmers have demonstrated that improving soil and water management using RWH technologies can effectively counter these risks.

However, in order to optimize the production potential of RWH technologies, practitioners and policy makers need to understand that there is no single technology-fit for all land and water management challenges. Rather they should strongly consider the multiple biophysical and socioeconomic stresses that interact to increase susceptibility and constrain adaptive capacities of RWH technologies. Thus, adapting technologies to specific local realities can enhance their replicability and scalability.

In addition, an integrated approach is needed to improve the productivity of rainfed agriculture in the ASALs. This can be realized by combining RWH with better soil fertility management, planting improved crop varieties, and where possible, supplementary irrigation using low-cost micro-irrigation technologies. However, in order to catalyse the rate of replication and scaling-up of RWH technologies, a participatory technology development and dissemination (PTDD) approach is important. An effective PTDD can act as a platform to acquire and transfer practical skills and knowledge and promote experiential learning which enables subsistence farmers to innovate and adapt new RWH technologies to local conditions.

## 5 Conclusions and Recommendations

It is evident that RWH technologies provide huge potential for subsistence households to improve climate resilience. The experiences discussed in the paper provide useful lessons for development and humanitarian agencies that to support food security interventions that target the vulnerable. The findings provide useful lessons that practitioners need to consider while selecting appropriate RWH interventions. Taking into consideration, the range of biophysical and socioeconomic constraints will assist to catalyse adoption, applicability and replication potential of RWH technologies.

In view of this, the following recommendations are proposed:

1. Promote the use of participatory technology development and dissemination approach to accelerate replication and scaling-up of RWH technologies.
2. Improving the design and implementation of RWH technologies to ensure they fit within local biophysical and socioeconomic contexts.
3. Forge ties with government institutions to improve access to advisory support in order to optimize the productive potential of RWH technologies.
4. Enhance linkages with research organizations to help fine-tune old technologies in ways that enhance their efficiency in contributing to sustainability.
5. Promote a mix of low-, medium- and high-tech technologies to balance the contrasting challenges of technology selection, cost, social acceptability, adoption, adaptation and diffusion.
6. Invest in building strong community institutions or farmer organizations.
7. In order to chances of success, practitioners should focus on replicating and transferring cost-efficient small-scale RWH technologies.

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