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.

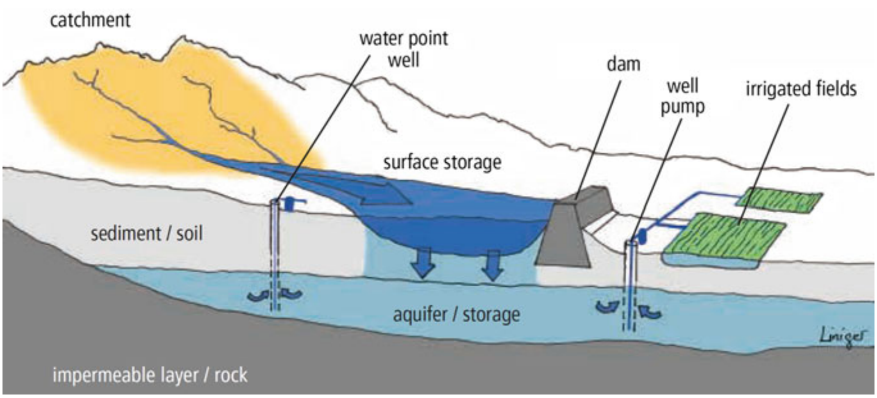

Fig. 1 Example of a RWHI system showcasing a macro-catchment RWH system linked to a pumping and small-scale irrigation system. *Source* Studer and Liniger (2013)

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 Buffering rainfall variability Reducing production risks, thus reducing vulnerability Optimising yield per unit of water Optimising the natural biophysical capacity of arid and semi-arid areas by means of the collection, storage and reuse of locally available rainfall 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 Supply can be limited by storage capacity, design and costs Some RWHI systems may take up productive land 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 Flexibility and adaptability High-value crops production Alleviating poverty: when adopted at scale Reducing migration to the cities Increase in school performance	Relatively high initial investments for most RWHI systems Low affordability for smallholder farmers Requires access to financing mechanisms 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 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 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 Community-based structures can lead to rights issues (upstream–downstream, farmers and herders) and maintenance disagreements Maintenance of communal infrastructures is complex Long-term institutional support is necessary 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.

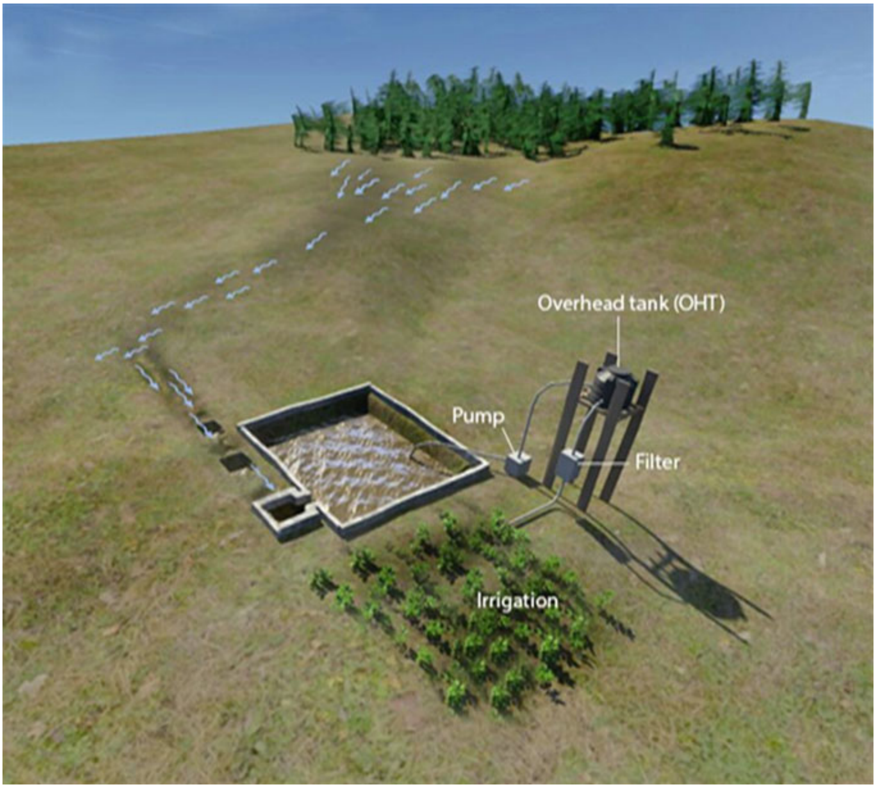

Fig. 2 On-farm pond system with an off-season small-scale irrigation system. *Source* Pixiniti Studios

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

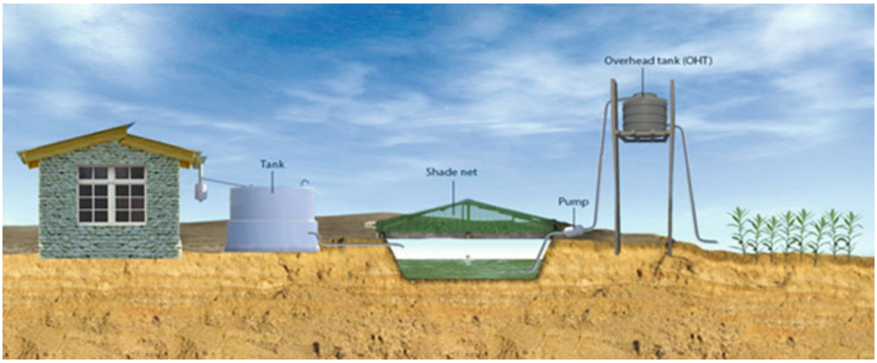

Fig. 3 Roof catchment system coupled with an on-farm pond and a water tank (optional). *Source* Pixiniti Studios

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)

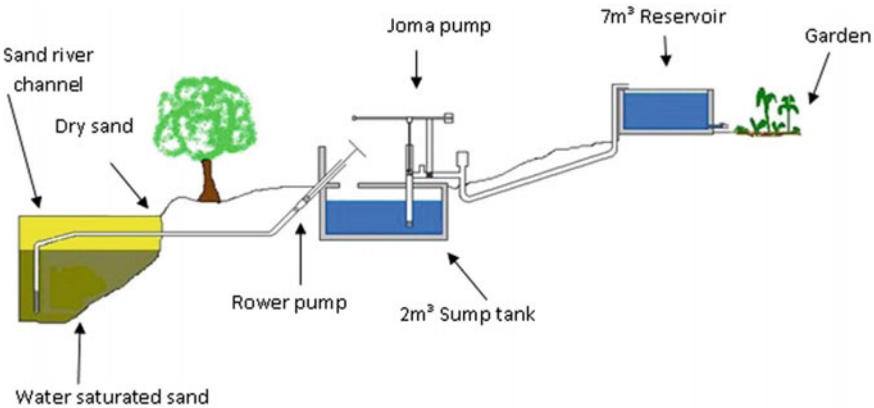

Fig. 7 Sand abstraction system to tap into natural shallow groundwater in seasonal sandy streams. *Source* Dabane Trust

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.

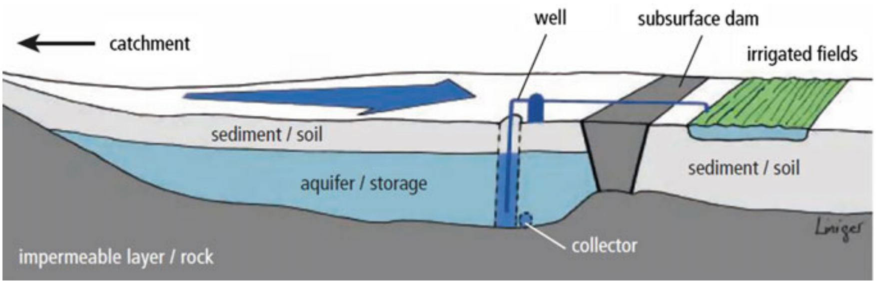

Fig. 8 Diagram of a subsurface dam. *Source* Studer and Liniger (2013)

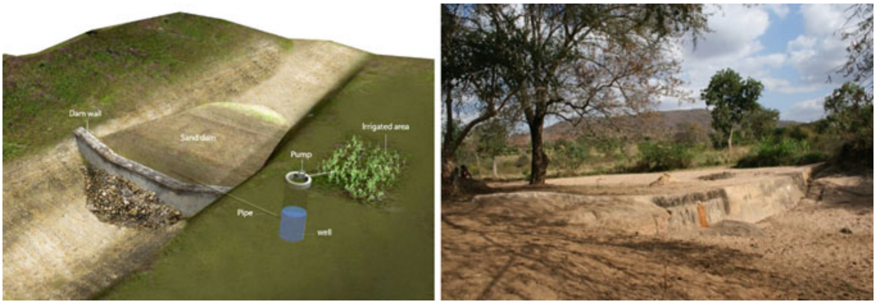

Fig. 9 Increase in sand sediments on the original riverbed caused by the construction of a sand storage dam: a diagram (left) and a real-life example (right). *Source* Pixiniti Studios. *Photograph* Josep de Trincheria Gomez

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 • Relative technical simplicity • Manual construction process • High acceptability, adoption and self-replicability • High suitability with road catchments, which produce large volumes of runoff • High suitability for manual pumping	• Vulnerability to evaporation, i.e. roofing is required • Vulnerability to seepage losses, i.e. dam liner is required • Roofing structures and dam liners are vulnerable to damage, need regular maintenance and repair, and eventually, need to be replaced (approx. 5–10 years) • Vulnerability to siltation, and health and safety risks	• Upgraded on-farm ponds with low evaporation, seepage and siltation losses • Link with road catchments and roof catchments • Access to community-based financing mechanisms supported by business activities • Link with national/ international multi-year funding programs • 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 • Limited irrigable area • High capital investment costs • Low resilience to poor rainfall years • Low natural recharge and low integrated restoration potential at the watershed level	• Adoption of reliable and efficient manual pumping systems • Adoption of low-cost drip and other improved irrigation systems
Roof catchments + Manual pumping + Low-cost drip irrigation	• High rainwater collection efficiency • High suitability for individual households • High acceptability and self-replicability • Provision of high-quality water for domestic uses • Low evaporation and siltation risks • Low health and safety risks • Low dependency on the characteristics of the terrain • High suitability for government buildings, schools and churches • High suitability for manual pumping and water application systems	• Limited yield and supply capacity, especially with water tanks and rock dams • Limited irrigable area • High capital investment costs • Low cost-efficiency • Low resilience to poor rainfall years • Leakage risks • Isolated system: no natural recharge or integrated restoration potential at watershed level	• Suitability for kitchen gardening and other income-generating activities at household level • Link with on-farm ponds for off-season micro- and small-scale irrigation • Low-cost ferro-cement tanks should be prioritised • Link with government buildings, schools and churches for off-season small-scale irrigation • Adoption of reliable and efficient manual pumping systems • 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 • High cost-efficiency • Flexible construction process suitable for local communities: manual/animal/ mechanical • Flexible and adaptable designs • High acceptability and adoption • High suitability with road catchments • High natural recharge and integrated restoration potential at the watershed level	• High evaporation losses • High siltation, health and safety risks • High capital investment costs • Low resilience to poor rainfall years and droughts • Conflicts between irrigators and pastoralists • Must be communally owned and managed • Low suitability for manual pumping and manual water application systems	• Link with road and rock catchments • Access to community-based financing mechanisms supported by business activities • Link with national/ international multi-year funding programs • Adoption of reliable and efficient mechanised pumping systems • 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 • High cost-efficiency • Resilience to poor rainfall years and droughts • High potential for off-season small-scale irrigation and income-generation activities • High acceptability • High natural recharge and integrated restoration potential at the watershed level	• High capital investment costs • Need to technical and financial external support • High technical complexity • Weak link with gravity-fed irrigation systems • Need of pumping systems • Low self-replicability • Must be communally owned and managed • Low suitability for manual pumping and manual water application systems	• Prioritise natural alluvial shallow groundwater and/or subsurface dams with water abstraction systems • Sand storage dams must be built by stages of reduced height to minimise siltation • Access to community-based financing mechanisms supported by business activities • Link with national/ international multi-year funding programs • Adoption of reliable and efficient

(continued)

Table 4 (continued)

System	Strengths	Constraints	Applicability/ scalability
			mechanised pumping systems • Adoption of low-cost drip and other improved irrigation systems
Rock catchments + Mechanised/ manual pumping + Low-cost drip irrigation	• Suitable in semi-desert environments • Resilience to poor rainfall years • High rainwater collection efficiency • Provision of high-quality water for domestic uses • Low health and safety risks • Relative technical simplicity • Potential for gravity-fed irrigation systems	• Limited yield and supply capacity • High capital investment costs • Limited irrigable area • Low cost-efficiency for water tanks • Must be communally owned and managed • 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 • Access to community-based financing mechanisms supported by business activities • Link with national/ international multi-year funding programs • 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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