AFRHINET

An ACP-EU Technology-Transfer Network on Rainwater Harvesting Irrigation Management for Sustainable Dryland Agriculture, Food Security and Poverty Alleviation in sub-Saharan Africa

ADVANCED TRAINING MATERIALS ON RAINWATER HARVESTING IRRIGATION MANAGEMENT IN ARID AND SEMI-ARID AREAS OF SUB-SAHARAN AFRICA

Technical capacity building on the use of rainwater for off-season small-scale irrigation in Ethiopia, Kenya, Mozambique and Zimbabwe

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CONTENTS

PROJECT BACKGROUND

AFRHINET 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 project specifically focused on the implementation of integrated capacity-building activities, the development of research and technology transfer activities, namely technology transfer centres and demonstration trials, and the setting-up of a transnational network of multivariate relevant actors. 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), Kenya Rainwater Association (Kenya) and MetaMeta Research (the Netherlands).

The four main core activities of the AFRHINET project were as it follows:

1. **Development of self-replicable capacities on RWHI management:** A two-phase capacity-building programme focusing on the scientific basis and the practical implementation of RWHI management. This was coupled with the development of training materials highlighting practical experiences and lessons learnt.

2. **Research and technology transfer centres:** The centres serve as hubs of knowledge and expertise in the field of RWHI management and dryland agriculture in rural areas of sub-Saharan Africa. Furthermore, they afford improved capitalisation and dissemination of innovative and effective RWHI management practices.

3. **Demonstration of innovative RWHI management:** Effective demonstrations relative to RWHI management did not only support, but also reinforced, the idea of alternative concepts to manage rainwater to local community groups, academic and scientific institutions, businesses/ micro-enterprises, and non-governmental and public organisations. The trials showcased the fact that implementing cost-effective RWHI projects for improved food security and poverty alleviation was feasible.

4. **Networking activities:** Strengthening the networking capacity of academic and scientific institutions with other relevant stakeholders at national and international level, in the field of RWHI management. This was coupled with regular international and national dissemination events.

1. INTRODUCTION

1.1 Background

Food insecurity have negative economic impacts, exacerbate poverty and poses today a problem to hundreds of millions only in the African continent, especially in rural communities of arid and semi-arid regions (UN, 2015). By mid-century, it is estimated that 9 billion people will require a 360 % increase in food production (Tesfaye et al., 2016). Inevitably, competition for energy, land and water will rise with growing food demand (Park, 2016). Much of this production will have to be derived from rural smallholder production systems. Thereby, placing these systems at the heart of the sustainable development agenda (Nicol et al., 2015).

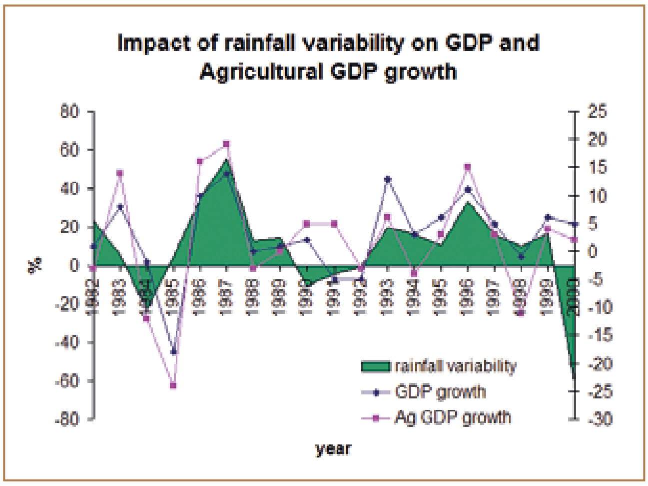


Figure 1: Correlation between GDP and rainfall variability in Ethiopia. Source: (World Bank, 2005).

Agriculture is a major economic activity in sub-Saharan Africa (FAO, 2014, 2015a). Thus, employment in agriculture is high, with values in eastern and southern Africa of 70 % in general (FAO, 2014) and 61 % for Kenya, 89 % for Ethiopia, 80 % for Mozambique and 60% for Zimbabwe in particular (FAO, 2015a). These trends are expected to continue beyond 2030 even with continued economic transformation (AGRA, 2016). Currently, the value added of agriculture to GDP is 30% for Kenya and Mozambique, 42% in Ethiopia, and 14% in Zimbabwe (FAO, 2015a). In addition, GDP growth generated by agriculture has been recognized as at least twice as effective in reducing poverty as growth generated by other sectors (WB, 2007). Therefore, the expansion of the economy as a whole, and the eradication of poverty in particular, are critically dependent on agriculture (UNDP, 2016). Yet, rainfed agriculture continues to bear the largest burden of generating food in sub-Saharan Africa (Falkenmark and Rockström, 2004) and it is inherently linked to GDP, as it is shown in Figure 1. While there is a constellation of factors responsible for poor performance of rainfed agriculture in sub-Saharan Africa, seasonal soil moisture scarcity is a major factor constraining this 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. For example, 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). In addition, this situation is currently aggravated by climate change (Pachauri et al., 2014), which increases rainfall variability, water scarcity, soil degradation and food insecurity, among others (Nicol et al., 2015). Climate change and variability is already reducing agricultural productivity and opportunities for employment, pushing up food prices, and affecting food security and health (UNDP, 2016).

The challenges mentioned earlier 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. Further, increasing production on existing agricultural land by managing rainwater resources more efficiently, placing less pressure on the environment and sustaining future capacities is thus seen as an important solution to meet current and future global food needs, and stays high on the global policy agenda (Nicol et al., 2015; Rockström and Falkenmark, 2015). For example, it has been estimated that if 15% of the rainwater in sub-Saharan Africa were harvested, it would be enough to meet all water-related food security needs of the continent (Malesu et al., 2006). Also, upgrading rainfed agriculture by means of rainwater harvesting techniques can double smallholder yields in drought-prone regions (Oweis et al., 1999; Dile et al., 2013).

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 are 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). As agriculture is the most important source of rural livelihoods in Africa, which constitute 70 % of the total population in sub-Saharan Africa (FAO, 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). Therefore, off-season small-scale irrigation has a very significant potential for food security, poverty alleviation and rural development (Malesu et al., 2006; Rosegrant et al., 2006; De Fraiture and Giordano, 2014; Wilchens, 2014).

Among others, improved irrigation could contribute halving the world's food gap, which is necessary to eradicate hunger worldwide by 2050 (Bacha et al., 2011). Further, production could increase by an average of more than 55 % in sub-Saharan Africa, which would be possible without expanding the area of land being farmed (Bacha et al., 2011). 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. Indeed, Bacha et al. (2011) found that the incidence, depth, and severity of poverty were significantly lower among those households with access to irrigation. Nicol et al. (2015) found that small-scale irrigation in Kenya gives good profits: compared with farm incomes from rainfed land, which average less than USD 750/ha per year, irrigated land can produce three crops a year worth USD 1,400/ha (snow peas, French beans), USD 450/ha (kale) or USD 600/ha (onions).

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-seaon small-scale irrigation (De Fraiture and Giordano, 2014). Thus, in many countries the area under privately managed and owned irrigation is larger than under public irrigation schemes (De Fraiture and Giordano, 2014). In fact, much of the investment in small-scale water extraction devices and irrigation equipment in sub-Saharan Africa has been made by individual farmers, without involving a formal irrigation scheme or a water user association (De Fraiture and Giordano, 2014; Wichelns, 2014). These facts reflect the strong interest of local communities to engage in off-season irrigation on one hand, and that the investment and operational costs of off-season small-scale irrigation can be affordable to individual farmers (Malesu et al., 2006).

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). In fact, using rainwater for off-season small-scale irrigation (RWHI) is a key component of rainwater-smart agriculture (Leal and de Trincheria, 2017). Rainwater-smart agriculture is a set of practical strategies specifically focusing on the optimisation of locally available rainwater resources in arid and semi-arid areas but integrating relevant water- and climate-smart agriculture approaches, as proposed by Nicol et al. (2015). Thus, numerous and diverse farming approaches promote the sustainable management of soils with the goal of improving soil fertility, agricultural productivity and climate resilience, among others, landscape management, smart-agroforestry, agroecology, conservation agriculture, and zero tillage farming (Ngigi, 2003; FAO 2015b,c).

According to De Trincheria et al. (2016a), RWHI management is defined from a technical viewpoint as a sub-set 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. Thus, RWHI management differs from the use of rainwater for supplemental irrigation because it is specifically meant to conduct off-season small-scale agricultural activities, especially kitchen gardens, trees, and high-value horticultural crops along riverbanks.

RWHI technologies and practices could contribute increasing global production by 41 % and close the water-related yield gap by 62 % (Jägermeyr et al., 2016; Park, 2016). This would be coupled with a diversification of the income-generating activities which would improve the livelihood potential in rural areas and alleviate poverty. Among other positive impacts, this could not only reduce forced rural migration to rural areas but contribute reversing back previous rural migrants (Woldearegay, 2016). In fact, a holistic strategy that focuses on raising organic matter and moisture retention coupled with the use of rainwater harvesting for off-season small-scale irrigation can increase food security, alleviate poverty and restore degraded lands on one hand, and buffer negative climate change and variability impacts during the next century on the other (Bacha et al, 2011; Pachauri et al., 2014; FAO, 2015b,c; Nicol et al., 2015).

However, the use of rainwater for off-season small-scale irrigation in arid and semi-arid areas is not exploited sufficiently in terms of agricultural and livelihood improvements on one hand, and technological development and market/ institutional adoption on the other. One of the key factors which is contributing to poor adoption, replication and transfer of RWHI technologies and practices is a lack of technical capacity to implement these systems in a cost-efficient manner. Thus, in order to realise the benefits of RWHI management, the systems must be designed and constructed professionally and be properly maintained. Adequate technical skills are also required to facilitate a strategic cost-efficient planning, implementation, monitoring and evaluation of RWHI systems. This is meant to ensure the highest return on investment in the system. Therefore, there is a need to increase the capacity of public and private practitioners, scientists and academics in order that that they can design, operate and maintain RWHI systems, and where possible, introduce local innovations to fit particular circumstances and preferences. This can enable wide adoption of RWHI technologies and ultimately increase the resilience of small-scale farmers in arid and semi-arid areas (Rockström et al., 2004). The technical capacity of local communities in arid and semi-arid areas, especially local artisans, smallholer farmers and enterpreneurs, also needs to be strengthened in order to soundly replicate and scale up rainwater harvesting management. However, the information and know-how they require should be tailored to their demands and needs. Due to this fact, the AFRHINET project has also developed a set of training materials that specifically focus on local communities. The materials are accessible at **http://afrhinet.eu/materials.html**.

1.2 Goals and objectives

These advanced training materials have been produced to foster the capacity of practitioners from private, non-governmental and public sectors on one hand, and academics and scientists on the other, to practically implement cost-efficient RWHI technologies and practices in arid and semi-arid areas.

Therefore, these training materials intend to provide the required information to support proper planning, design and construction of cost-efficient RWHI technologies and practices, with special emphasis on the specific problems encountered in Ethiopia, Kenya, Mozambique and Zimbabwe. Further, this manual also suggests relevant technical manuals which specifically focus on each of the RWHI technologies and practices. It is strongly recommended that reference is also made on this additional materials with help from experienced professionals in this field of knowledge.

1.3 Structure

The training materials are divided in 10 chapters which specifically address all relevant technologies and practices that can be used to collect, store and reuse rainwater for off-season small-scale irrigation. Therefore, other uses of rainwater to enhance rainfed agriculture, especially rainwater for supplemental irrigation, or among others, in-situ and micro-catchment RWH systems that are not specifically meant to be used for off-season small-scale irrigation, are not considered. The manual contains some pictures and technical drawings which are borrowed from relevant scientific and technical literature. In addition, some of the content materials included in this manual have been used with the courtesy of ASAL Consultants (http://www.waterforaridland.com/), Dabane Trust (http://www.dabane.org/), Kenya Rainwater Association (http://www.kenyarainwater.org/), the Roads for Water Learning Alliance (http://roadsforwater.org/) and SEARNET-ICRAF (http://www.searnet.net/), among others.

It is not necessary to use the entire manual, although chapter 2 has been designed to be of interest to all RWHI technologies. Chapters 3 to 10 can be used as a reference guidelines for each of the specific RWHI technologies and practices that are highlighted in this manual. Further, complementary training materials linked to this manual are the presentations given as part of the 1-week advanced capacity building courses on RWHI management in Ethiopia, Kenya, Mozambique and Zimbabwe. The course materials are accessible through the AFRHINET website at **http://afrhinet.eu/materials.html** or the specific country sections of the AFRHINET virtual Technology Transfer Centres at **http://www.rainwatertechcentres.net**/.

2. USING RAINWATER FOR OFF-SEASON SMALL-SCALE IRRIGATION IN ARID AND SEMI-ARID AREAS

2.1 Rainwater harvesting management for food security

Local communities in arid and semi-arid areas have since ancient times under varying ecological conditions harvested rainwater to secure or increase agricultural production (Prinz, 2002). Recently, a wide variety of techniques for collecting, storing, and reusing natural precipitation for agricultural purposes have gained momentum at a global level (Biazin et al., 2012). Agricultural uses mainly include the production of crops, livestock, fodder and trees (Biazin et al., 2012). In-situ techniques and appropriate land management practices, which enhance infiltration and reduce surface runoff and soil evaporation, are also included as rainwater harvesting management techniques (Rockström et al., 2001). In this study, the term rainwater harvesting (RWH) management for food security has been used to encompass all practices of rainwater collection, storage and efficient reutilisation for crop and/or livestock production (Rockström et al., 2001; Ngigi et al., 2005; Biazin et al., 2012). Among them, supplemental and off-season small-scale irrigation, spate irrigation, and other practices to increase soil moisture and shallow groundwater recharge for agriculture. As it is shown in Figure 2, RWH technologies for food security are classified in three main categories (Biazin et al., 2012).

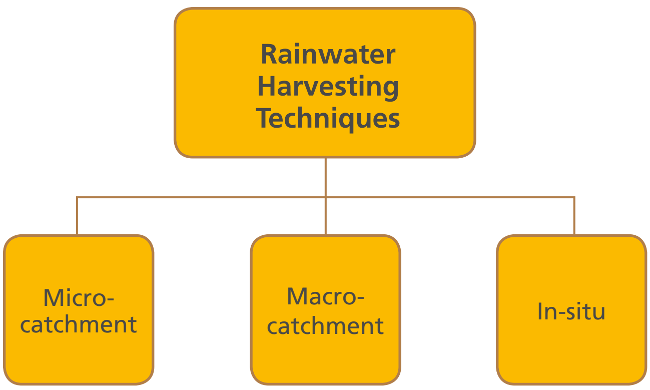


Figure 2: Classification of RWH systems for food security.
Source: (De Trincheria et al., 2016a).

1. **Micro-catchment RWH systems:** Collection of surface runoff from small catchment areas with water storage in the soil for rainfed agriculture and/or dry-spell mitigation.

2. **Macro-catchment RWH systems:** Collection of surface runoff from large catchment areas with water storage for supplementary and/or off-season irrigation, spate irrigation, and/or livestock watering.

3. **In-situ RWH systems:** Techniques applied in the crop area in order to maximise infiltration, reduce surface runoff and soil evaporation, and improve soil fertility and water availability.

2.2 Rainwater harvesting management for off-season small-scale irrigation

Rainwater harvesting for off-season small-scale irrigation (RWHI) is defined as a set of technologies and practices that allows 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, trees, 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). Thus, it is usually used to increase and stabilise the yield of rainfed crops during critical growth stages, and therefore, it is not considered to be an off-season practice. 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 in order to distribute and conserve the moisture within the root zone of plants (van Steenbergen et al., 2010). Thus, spate irrigation systems (i.e. without storage systems) are not specifically designed to facilitate the practice of off-season irrigation. However, both rainwater for supplemental irrigation and spate irrigation have an immense transformative positive potential and should be implemented always that it is feasible. Oweis et al. (1999) and van Steenbergen et al. (2010) should be used as a reference to implement these type of technologies and practices, respectively.

RWHI management is predominantly designed to sustain subsistence agricultural activities during dry periods at the smallholder level. It is suited to be practiced 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 3 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 undergroud reservoir, usually around 25 m^3 to 1,000 m^3.

3. A low-cost irrigation system that applies water to the crop area during dry periods.

It is worth considering that 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.

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, each technique has a unique scope due to hydrological, technical and socio-economic factors, as it is described in detail in chapters 3 to 10.

2.2.1 Examples of macro-catchment RWH systems

This type of technologies collect surface runoff from external catchments and store it for further use during dry periods

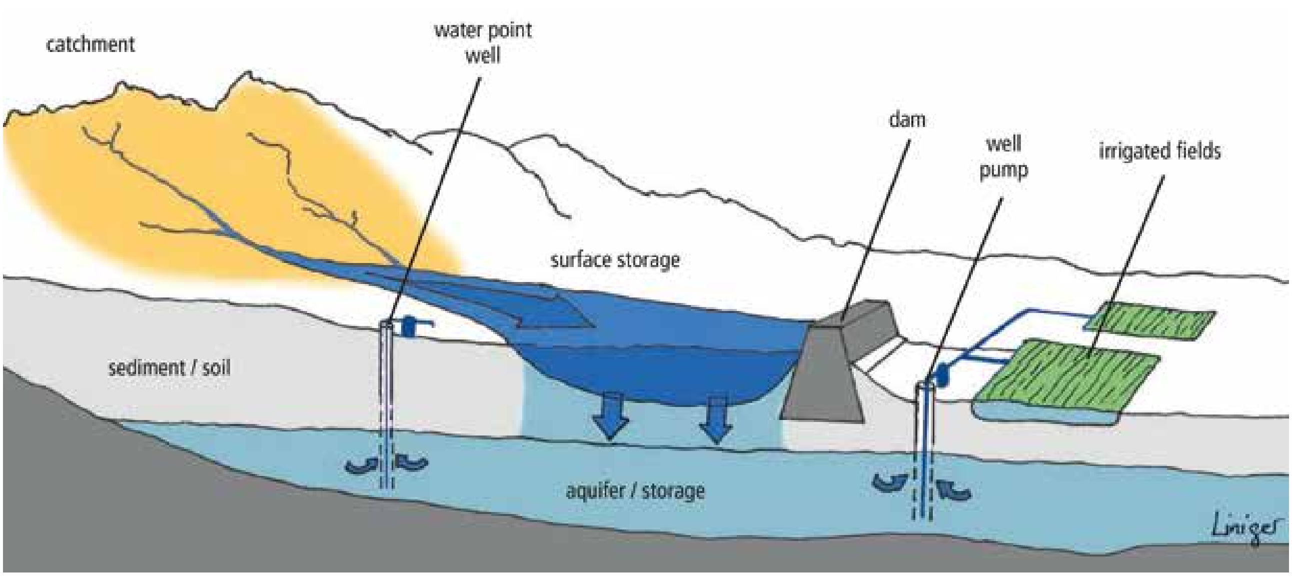


Figure 3: An example of a RWHI system showcasing a macro-catchment RWH system linked to a pumping and small-scale irrigation system.
Source: (Studer and Liniger, 2013).

Table 1: Potential of macro-catchment RWHI systems to be used for off-season small-scale irrigation. Potential: High (+++), Medium (++), Low (+). Source: Adapted from De Trincheria et al. (2016a).

RWH Storage Technology	Ethiopia	Kenya	Mozambique	Zimbabwe
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	+ +	+ +	+ +	+ +
Surface dams and perennial riverbeds	+	+	+	+

(Hatibu et al., 2000; Biazin et al., 2012). Rainwater/run off is collected from existing paved surfaces (e.g. roads and/or rooftops) and natural slopes and/or streams, and at a lower extent from purpose-built structures (Biazin et al., 2012). The catchment type and area, and the storage volume, depend on local rainfall patterns and soil types, among others (Studer and Liniger, 2013). Several of the widely applied macro-catchment RWH systems are indigenous or modified from indigenous practices (Biazin et al., 2012), which usually increase their acceptability among local communities.

Table 1 shows the off-season small-scale irrigation potential of relevant macro-catchment RWH technologies that are currently implemented in Ethiopia, Kenya, Mozambique and Zimbabwe.

Most configurations for RWHI storage technologies are relatively common in sub-Saharan Africa in general, and Ethiopia, Kenya, Mozambique and Zimbabwe in particular. In addition, macro-catchment RWH systems include traditional and improved surface dams being promoted by local communities, governments, private sector and NGOs.

Rainwater harvesting from tanks, ponds and earth dams are a common RWH technology in sub-Saharan Africa. In most of the cases, the catchment area of these systems are roads. Thus, road catchments provide a highly cost-efficient collection of runoff that can be linked to small-scale irrigation by means of different storage systems. On-farm ponds have been introduced in many parts of Ethiopia through a government-subsidised dam liner initiative (Fentaw et al., 2002). Also in Rwanda (Malesu et al., 2010) and Kenya (Odhiambo, 2016). Research findings have shown that on-farm ponds for off-season small-scale irrigation have produced promising results (Rockström et al., 2001; Ngigi et al., 2014; Bouma et al., 2016). However, one of the remaining challenges lies in designing simple and cost-effective on-farm ponds that allow gravity-fed irrigation and reduce the cost of pumping water for off-season irrigation (Ngigi, 2003). At community level, small earth dams are constructed to store large quantities of water, especially for livestock and small-scale irrigation.

Major challenges with regard to the storage of water in arid and semi-arid areas are seepage, evaporation and siltation. Thus, underground water tanks with 50 m^3-100 m^3 storage capacity were introduced in Laikipia County (Kenya) in the late 1980's. However, loss of water through seepage was identified as a major drawback in these systems (Kihara, 2002; Ngigi et al., 2005) and various strategies are still being implemented to minimise water losses. These include sealing the tank surface with polythene lining, mortar, rubble stones or clay in order to reduce seepage losses, and covering the tanks to minimise evaporation losses. Nonetheless, similar initiatives in Kitui County (Kenya) were discouraging as most of the masonry underground tanks ended up cracking and hence being abandoned (Ngure, 2002). In fact, despite potential positive impacts, technology adoption and scaling up can be hampered if simple seepage control measures are not implemented (Ngigi, 2003). This is evident from experiences in Nakuru and Machakos County (Kenya), where naturally impermeable clay soils have resulted in high adoption rates of unlined farm ponds (Malesu et al., 2006; Masika, 2015). In areas with permeable soils, farmers have experimented with various seepage control methods, among them, normal plastic lining (not found durable), bitumen lining, clay lining and even goats' trampling. While concrete sealing has worked well in some areas, high construction costs have led to low adoption rates. Nevertheless, the availability of various grades of ultra-violet resistance plastic lining material (dam liners) seem to be a cost-effective and sustainable solution. Pilots carried out by the ICRAF-RELMA project proved that a 0.8 mm liner has a lifespan of 12 years. In addition, on-farm ponds in Ethiopia and Kenya are covered by a roof to reduce evaporation losses and/or specifically designed to reduce evaporation. However, such configurations are not common in Mozambique and Zimbabwe. Also, several physical mechanisms to reduce siltation, especially silt traps, are available.

Another system with high potential used in Kenya, and at a lower extent in Ethiopia, Zimbabwe and Mozambique, are groundwater dams. However, their link to small-scale irrigation is generally untapped, with some exceptions in Kenya and Zimbabwe, where a small number of groundwater dams are being used to irrigate community-based vegetable gardens. If not adequately designed, these systems are vulnerable to siltation, seepage and evaporation.

Rock catchment systems capture runoff from rock surfaces, with storage capacities ranging from 25 m^3 - 4,000 m^3. Their replication is rather limited in sub-Saharan Africa with the exception of Kenya. In addition, rooftop catchment systems present a wider distribution but show significant lower storage capacities, which make them strictly suitable at the household level. Both systems are generally used for domestic purposes, but can also be used for kitchen gardening (Ngure, 2002; Ngigi and Denning, 2010). Further, these systems show high potential to be used for small-scale irrigation if specifically connected to small earth dams (rock catchments) and on-farm ponds (roof catchments).

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. Among others, infiltration pits and percolation ponds show high potential to naturally recharge groundwater levels. Also, micro-catchment and/or in-situ RWH systems inherently increase the soil moisture of the crop rooting zone during wet periods. Thereby, potentially enhancing off-season irrigation during dry periods.

2.2.2 Examples of micro-catchment RWH systems

According to Biazin et al. (2012), a micro-catchment rainwater harvesting system collects runoff within the farm boundary from relatively small catchment areas from 10 m^2 to 500 m^2. The most commonly applied micro-catchment rainwater harvesting techniques in sub-Saharan Africa include pitting, contouring, terracing and micro-basins (Motsi et al., 2004; Nyamangara and Nyagumbo, 2010; Biazin et al., 2012; Malesu et al., 2012; Nyamadzawo et al., 2013). These type of technologies are more widely implemented in Ethiopia and Kenya as compared to Zimbabwe and Mozambique. Table 2 shows a selection of relevant micro-catchment technologies for RWH that are currently implemented in Ethiopia, Kenya, Mozambique and Zimbabwe.

2.2.3 Examples of in-situ RWH systems

In-situ systems involve the use of practices that increase infiltration, reduce runoff and evaporation, and improve soil moisture directly in the crop rooting zone by trapping and holding the rain where it falls (Hatibu et al., 2000; Ngigi, 2003; Gebreegziabhert et al., 2009; Nyamangara and Nyagumbo, 2010). The most commonly applied in-situ rainwater harvesting and management practices in sub-Saharan Africa include ridging, mulching, various types of furrowing and hoeing, and conservation tillage (Biazin et al., 2012).

Table 2: Relevant micro-catchment technologies for RWHI in Ethiopia, Kenya, Mozambique and Zimbabwe. Distribution: High (+++), Medium (++), Low (+). Source: adapted from Biazin et al. (2012) and De Trincheria et al. (2016a).

Micro-catchment RWH	Description	Ethiopia	Kenya	Mozambique	Zimbabwe
Pitting: Different types of planting pits and trenches	Grid of planting pits are dug across plots or along the contours with or without bunds downslope	+ + +	+ + +	+	+ + +
Contouring: Stone and soil bunds, hedge rows and vegetation barriers	Stones or earthen bank is piled on a foundation along the contour in a cultivated hill-slope, sometimes stabilized with vegetation.	+ + +	+ + +	+	+
Terracing: Fanya juu, semi-circular and hillside terraces	Bunds in association with a ditch, along the contour or on the lateral of a gradient which are constructed in different forms	+ + +	+ + +	+	+ +
Micro-basins	Different shapes of basins surrounded by low earth bunds	+ + +	+ + +	+	+

Table 3: Relevant in-situ RWH systems practices in Ethiopia, Kenya, Mozambique and Zimbabwe. Distribution: High (+++), Medium (++), Low (+). Source: adapted from Biazin et al. (2012) and De Trincheria et al. (2016a).

In-situ RWH	Description	Ethiopia	Kenya	Mozambique	Zimbabwe
Furrowing	Different furrowing techniques are used before or after planting in order to conserve soil and water. Fertilisers are usually used in conjunction	+ + +	+ + +	+	+
Ridging	Basins wider than traditional furrows are implemented using a modified ploughing instrument	+ + +	+ + +	+ +	+ + +
Mulching	The use of crop residues and other materials like stones which are aimed at covering the soil and improve water infiltration	+ +	+ +	+	+
Conservation tillage	A wide range of tillage techniques meant to increase soil moisture and enhance crop production	+ + +	+ + +	+ +	+ + +

Various studies suggest that in-situ rainwater harvesting in combination with improved soil fertility and good agronomic practices has the potential to unlock rainfed crop production systems (Ngigi, 2003; Mati, 2007; Kathuli et al., 2010; Nyamangara and Nyagumbo, 2010; Nyagumbo et al., 2011; Malesu et al., 2012; Nyamangara et al., 2013). Table 3 shows a selection of relevant in-situ RWH systems that are currently implemented in Ethiopia, Kenya, Mozambique and Zimbabwe.

2.2.4 Examples of off-season small-scale irrigation systems

Wichelns (2014) found that in sub-Saharan Africa, smallholders mainly invest in buckets, watering cans, drip irrigation kits, pipes, manual pumps or small motorized pumps. Currently, the predominant water sources are nearby rivers, canals, reservoirs or shallow wells but there is huge potential to tap into rainwater for off-season small-scale irrigation.

The most common small-scale irrigation method in sub-Saharan Africa is manual irrigation by means of watering cans, buckets or jerry can (Fraiture and Giordano, 2014; De Trincheria et al., 2016a). Water can also be applied through a spout fitted with a shower rose. Manual irrigation is widely practiced in the production of garden vegetables and where the water source is near the garden. In addition, most smallholder irrigation schemes in sub-Saharan Africa usually apply surface irrigation (De Fraiture and Giordano, 2014). These methods involve the diversion of water from streams and dams by gravity or mechanised pumping. The water is then conveyed by means of mainly open channels or pipes to the cropped area. Canals, which are lined or unlined, are also used to direct water into the fields. Unlined canals are popular among the resource-poor farmers because of low initial costs. Water can also be conveyed to the fields by using pipes fitted with or without sprinklers. The pipes vary in different sizes and can be moved from one position in the field to another (De Trincheria et al., 2016a).

Table 4: Relevant small-scale irrigation technologies commonly practiced in the countries under study. Distribution: High (+++), Medium (++), Low (+). Source: (De Trincheria et al., 2016a).

Small scale RWHI Technology	Ethiopia	Kenya	Mozambique	Zimbabwe
Watering can / bucket	+ + +	+ + +	+ + +	+ + +
Surface irrigation	+ +	+	+	+ +
Manual pumping	+ +	+ +	+ +	+ +
Mechanised pumping	+ +	+ +	+ +	+ +
Sprinkler system (single drag hose)	+	+	+	+
Drag Hose irrigation (no sprinklers)	+	+	+	+
Low-Cost drip irrigation kits	+	+	+	+
Ox-drawn / tractor-drawn bowsers	+	+	+	+

Table 5: Key advantages and disadvantages, and overall impacts of RWHI management.
Source: (Oweis et al. 1999; Ngigi, 2003; Payen et al., 2012; Studer and Liniger, 2013; Ngigi et al., 2014; JICA, 2015).

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. • RWHI systems contribute to the natural recharge of groundwater levels, which has 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 1,200/year. With a green house can earn up to USD 2,500/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 that 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.	• Ponded water can be 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 communities.
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 requires technical and engineering skills to ensure proper planning, hydrological assessments, siting/topographical survey, designing, construction 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. Thus, long-term institutional support is necessary. • Establishment of operation and maintenance systems for water resource management is inevitable for sustainable use of precious resources.

A specific type of small-scale irrigation system with high potential revolves around the use of micro-irrigation systems (De Trincheria et al., 2016a). These mainly involve low-head, low-cost drip (LHLCD) irrigation kits for smallholder farmers. LHLCD kits range from 20-L bucket kits to 200-L mini-tank systems that operate at 0.5 to 1 m water head and irrigate up to 2000 m^2 (Ngigi, 2009). De Fraiture and Giordano (2014) found that LHLCD kits that irrigate up to 500 m^2 are marketed for around USD 250. With drip systems, plants receive water through emitters that produce droplets of water, thereby, wetting the soil around the plant root zone (Ngigi, 2003). The simplest is a "bucket drip kit", which is made up of a bucket, a filter, connectors and a drip tape. Farmers commonly use the system in kitchen gardens (Kaluli et al., 2005). Other types of micro-irrigation systems are based on vegetable gardens that are manually irrigated and/or use simple manual pumps to lift water from a small reservoir usually located nearby the farm (De Trincheria et al., 2016a).

Manually operated pumps such as treadle pumps have not been adopted at large scale, despite social marketing efforts by international NGOs (De Fraiture and Giordano, 2014). These authors also found that the adoption of water pumps which are coupled to diesel- and petrol-powered engines in sub-Saharan Africa has only recently started to take off, but the technology is spreading steadily. In Ethiopia, a conservative estimate of 400,000 pumps were imported from 2002 to 2012 (De Fraiture and Giordano, 2014). Further, solar-powered pumps are also increas-

Table 6: Specific impacts of the 3 main categories of RWHI systems. Importance: High (+++), Medium (++), Low (+), Neutral (+/-).
Source: Adapted from Studer and Liniger (2013).

	Macro-catchment RWHI systems	In-Situ and Micro-RWHI systems: Natural shallow groundwater recharge	Rooftop RWHI systems
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	+ + +	+	+
Nutrition and health	+ + +	+ + +	+ + +
Aquifer recharge	+ +	+ + +	+ / -
Maintaining and improving food security	+ + +	+ + +	+ + +
Reducing rural poverty	+ + +	+ + +	+ + +
Creating rural employment	+ + +	+ + +	+
Supporting gender equity	+ + +	+ + +	+ + +
Improving water productivity	+ + +	+ + +	+ + +
Climate change adaptation	+ + +	+ + +	+ + +
Resilience to extreme dry conditions	+ + +	+ + +	+
Resilience to variable rainfall	+ + +	+ + +	+ + +
Resilience to extreme rain	+ +	+ +	+ + +
Natural disaster prevention / mitigation	+ + +	+ + +	+
Resilience to rising temperatures and evaporation rates	+ + +	+ + +	+ + +

ingly being promoted by some NGOs. Ox-drawn bowsers mounted on wheels are also used for small-scale irrigation. The water bowsers are fitted with a tap on which a flexible pipe can be fitted.

The most widely practiced methods of irrigation in Ethiopia, Kenya, Mozambique and Zimbabwe are summarised in Table 4. The link between small-scale irrigation and rainwater harvesting comes when the rainwater stored during wet periods is used for off-season irrigation.

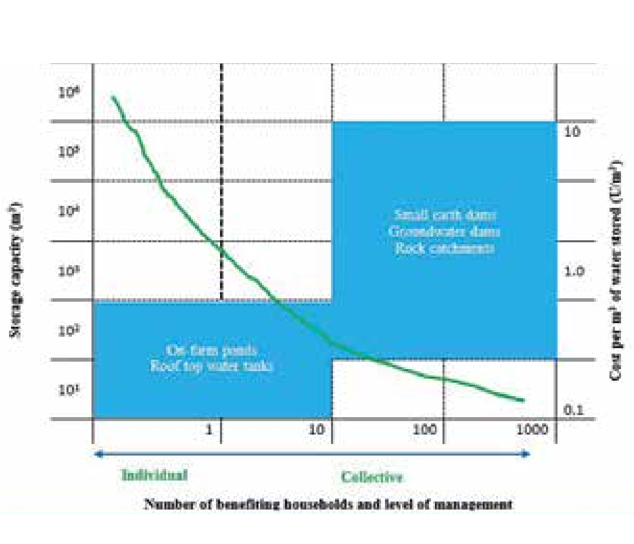


Figure 4: A range of water storage options, level of service and relative unit costs. Source: Adapted from Payen et al. (2012).

2.2.5 Advantages and disadvantages

Table 5 shows an overview of key advantages and disadvantages of RWHI management. Chapters 3 to 10 gives a detailed overview of strengths and weaknesses of relevant RWHI technology and practices.

2.2.6 Impacts

The overall impacts of RWHI management in arid and semi-arid areas are grouped into 4 key categories. In addition, Table 6 shows the contribution to specific impacts for each of the three groups of RWHI systems described in chapters 3 to 10.

1. Higher agricultural productivity and food security.

2. Higher household income and livelihood options.

3. Higher nutrition and health.

4. Higher resilience to climate variability and change.

2.2.7 Cost-efficiency

RWHI technologies and practices have different cost-efficiencies depending on multivariate factors, among others, the volume of water stored, the reliability of water supply and the construction costs (Payen et al., 2012). Figure 4 shows a comparison of different RWHI systems taking into account the rainwater/runoff storage, the costs per m^3 of stored water and the number of households benefited. Chapters 3 to 10 give detailed information about the cost-efficiency of relevant RWHI systems.

The type of water storage options and financial capability usually dictates the storage capacity for different households and/or communities. The larger the storage capacity for each type of option, the lower the unit cost per m^3 due to economy of scale, as it is shown by the green line in Figure 4. At household level, the investment decisions are limited by availability of financial options despite the farmers' willingness to increase water storage for agriculture. Farmers have few options due to their averseness to taking credit from financial institutions, and the high interest rates charged because of perceived risks of rainfed smallholder farming systems. As a result, many farmers hesitate to take any risk for fear of failure and falling into indebtedness (Payen et al., 2012). In addition, profitability and income for replication, operation and maintenance is determined by better marketing conditions for irrigated products. Very often, the performance of RWHI management is constrained by the difficulties that farmers face in marketing their production at an acceptable price.

2.2.8 Suitability and constraints

The success of any RWHI systems depends on many factors, i.e. siting, design and construction, technical capacity of the beneficiary, operation and maintenance requirements, capital investment costs, speed of investment recovery, and acceptability and ownership, among others. To address the challenges related to the overall implementation process of RWHI systems, i.e. siting, designing, constructing, operating and maintaining, the following factors need to be considered:

a) Technical and engineering factors.

b) High investment costs and low farmers' financial capability.

c) Inadequate local/community capacity.

d) Social and environmental issues.

These factors have to be addressed adequately to ensure that any RWHI system is able to perform cost-efficiently and produce optimal benefits to the beneficiaries without disrupting the ecosystem and social fabric of the community. In addition, RWHI technologies and practices are clearly site-specific. Therefore, their adoption, applicability and scalability are limited to biophysical and hydrological characteristics. This basically implies that each technology is applicable under different circumstances based on topography, landscape characteristics and the capacity of the community. Thus, the suitability of each RWHI system should be considered independently based on a situational analysis and technically viable options. Table 7 shows an overview of factors that determine the suitability of RWHI technologies. Chapters 3 to 10 focus in detail on these factors.

Table 7: Suitability factors of key RWHI systems.
Source: Adapted from Studer and Liniger (2013) quoting WOCAT (2012).

Applicability	Macro-catchment RWHI systems	Rooftop RWHI systems
Annual rainfall	> 200 mm.	>200 mm.
Water use	Suitable to off-season small-scale irrigation up to 2 ha.	Limited to horticultural and vegetable crops and trees in kitchen gardens and backyards.
Land	Catchments on slopes and application areas on flatter land and / or depressions.	All types.
General slope of catchment area	0 - 50 %.	Any slope but not too steep.
Runoff coefficient	Low-medium.	High.
Catchment surface	Treated and untreated.	Any impermeable roofing material.
Application area	Any.	Any.
Soils	Any.	Any.
Landscape scale	Operates at household and community level with impacts at the watershed level.	Household level.
Land / water use rights	Individual or communal land ownership, and communal water rights.	Individual.
Level of mechanisation	Manual and mechanised	Manual.
Labour requirements	High.	High.
Level of technical know-how: Implementation	High to medium.	High to medium.
Level of technical know-how: Maintenance	High to medium.	Medium.
Investment	High.	High.
External support: Finances, materials and technical.	High.	High.
Benefit to costs	Short term: Negative. Long term: Very positive.	Short term: Negative. Long term: Positive.
Risk reduction	High.	High.
Main constraints	Evaporation, seepage and siltation of storage structures. Stored water can become a source of waterborne diseases.	Costs of storage facility. Limited storage volume. Cross-contamination: Needs filtering and protection.

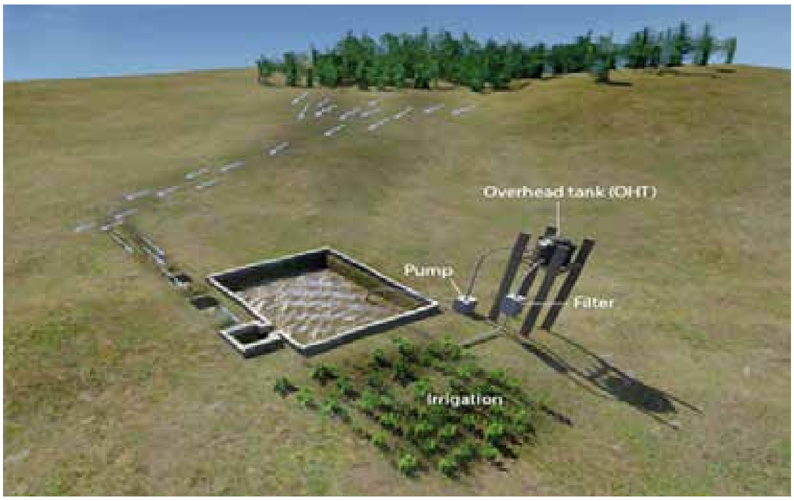
3. RUNOFF ON-FARM PONDS FOR OFF-SEASON SMALL-SCALE IRRIGATION

3.1 The technology

An on-farm pond is an excavated pit that acts as a runoff storage structure, mainly for micro/small-scale irrigation or kitchen gardening, as it is shown in Figure 5 (left). It is simple to construct and can be implemented in relatively flat terrains. The water storage capacity of an on-farm pond is limited by a number of factors such as size, amount of runoff generated, water losses (i.e. seepage, evaporation and siltation) and water use. In gently sloped areas, pond capacity can be increased by constructing an embankment across a watercourse using the excavated material. Farm ponds present different shapes and sizes depending on the soil type, i.e. irregular, circular, rectangular with vertical or slanted walls (trapezoidal), and different sizes depending on the beneficiary's financial capacity and intended water use, i.e. 25 m^3 to 1,000 m^3 for small-scale irrigation purposes (Ngigi and Oremo, 2015). In areas with impervious soils, the shapes of the ponds are often hemi-spherical and do not require lining. If the soil is pervious and porous, the ponds should be trapezoidal in shape and lined with geomembrane or compacted clay.

Household ponds are constructed to harvest runoff from the ground. The runoff is usually conveyed through roads and/or footpaths into the pond reservoirs. Thus, roads provide good catchment areas in which runoff is cost-efficiently generated in large volumes during rainfall events and are commonly used in connection with on-farm ponds, as it is shown in Figure 5 (right).

On-farm ponds have a high potential for off-season small-scale irrigation purposes at the household level. However, their success is limited by evaporation, siltation and seepage risks on one hand, and safety and health risks on the other, as it is shown in Figures 6 and 7. Therefore, there is a need to implement an upgraded on-farm pond



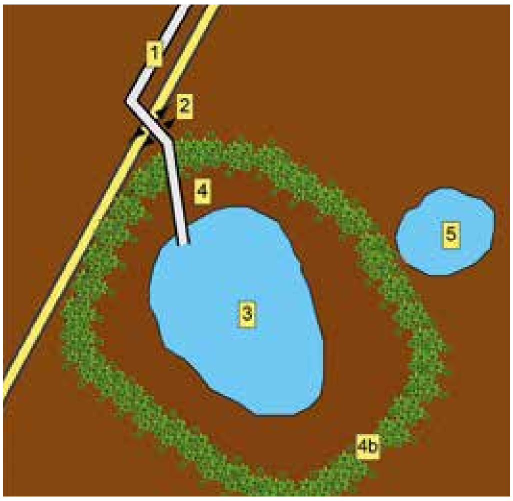


Figure 5: An on-farm pond system with an off-season small-scale irrigation system (left) and a road runoff pond (right).
Source: Pixiniti Studios (left), MetaMeta (right).

system that specifically takes into account these risks. This challenge led to the development of an upgraded farm pond which has been developed and promoted by Kenya Rainwater Association (KRA) and currently is being further replicated and scaled-up in cooperation with SEARNET-ICRAF and AFRHINET, among others.

Figure 6: On-farm ponds affected by poor workmanship.
Photos: S. Ngigi.

Figure 7: On-farm ponds affected by siltation, evaporation and seepage.
Photos: S. Ngigi.

Figure 8: Evolution of control measures for seepage and evaporation water losses.
Photos: S. Ngigi.

The upgrade is a runoff storage reservoir with an inverted trapezoidal shape (Figure 9), which should be connected to a road catchment. In addition, it is lined with a ultra-violet 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 with top and bottom dimensions of 8 m x 6 m, and 4 m x 2 m respectively, and a depth of 2 m with 1:1 side slope (Figure 9). Different storage capacities for the farm pond can be adopted up to 1,000 m^3 depending on water demand and the beneficiary's financial capacity.

The roofing is intended to minimise evaporation, 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 eases lifting of water from the farm pond into a low-head low-cost drip irrigation system. Further, to reduce siltation and improve water quality, a double chamber silt-trap that was adopted from Ethiopia has been incorporated. The silt trap is coupled with a screen filter that prevents floating debris from entering the farm pond. A real-life example of an upgraded on-farm pond system is shown in Figure 8.

3.2 Applicability and scalability

On-farm ponds are highly adaptable to a wide range of smallholder-based farming systems in sub-Saharan Africa. The technology is relatively simple to site and construct with minimal technical skills, and also simple to operate and maintain. The sizes are flexible and can be tailor-made for different landscapes, water requirements and users, and farmers' economic considerations. The technology is highly cost-effective and can be obtained as one RWHI package including low-head low-cost drip irrigation and a manual pump. It has however several key challenges, among them, the capital investment costs, which are not usually affordable by local communities. However, the on-farm pond RWHI system shows high potential: With a 50 m^3 pond, a smallholder farmer can recover the investment costs within 2 cropping seasons depending on the type of crops and market scenario, as it is shown in Table 8.

3.3 Siting

Siting is required to identify the most suitable runoff source, i.e. footpaths/road, roofs or grazing land, in relation to the location of the water reservoir and the irrigation field. Siting of the household farm ponds can be implemented through the use of local knowledge and/or the use of scientific-based expertise. In the first approach, the experience-based knowledge of the farmer with regard to runoff flow patterns is used to assess the catchment area and potential conveyance channels. This is coupled with

Table 8: Typical cost-benefit analysis on the impacts of on-farm ponds in Kenya.
Source: Adapted from Kenya Rainwater Association.

Item	Costs (USD, 2017)
Investment cost	
1. Farm pond (50 m^3)	1,000
2. Drip irrigation system with hand pump (0.5 ha)	2,000
3. Inputs (agro-chemical, labour, logistics)	500
Total Investment	3,500
Financing costs	
4. Loan interest (12 %)	480
Total annual financing cost	480
Income from annual horticultural production (2 wet periods)	
5. Net return from tomatoes (6 - 9 months)	1,810
6. Net return from capsicum (6-9 months)	2,530
Total seasonal income Year 1	4,340
Capital investment costs + financing	3,980
Revenues Year 1	360
Payback period	12 months

on-the-ground observations of technical staff during a 1-day field survey, if possible. The result is selecting the location of the pond taking into account the available space and runoff gravity flows.

The second approach revolves around deducting flow patterns emanating from contour lines as a result of a topographic survey of the farm. The survey should be done during the dry season using one of the methods highlighted below:

1. Low-cost equipment: Basically, the A-Frames, pegs and offsets. This is highly appropriate because it is low-cost, simple and produces accurate results if chaining or tape measures are used.

2. GPS sets to generate grid points for drawing contours: This is to determine the best location for the pond, i.e. where the lowest energy is required for water abstraction. The problem with GPS sets is that their resolution is low when dealing with small areas such as farms. However, this challenge can be minimised if sophisticated GPS tools are used.

3. Use of Dumpy levels, theodolites or total Stations: Contours lines can be drawn to determine the best location for the pond. Although this method is highly accurate, it is usually expensive to buy the tools and the method requires technical expertise. Alternatively, all required materials are easily available in any local government office of relevant disciplines (e.g. construction of hydraulic retention structures) and the corresponding local officercan carry out the necessary 2-4 h survey at relatively low costs.

3.4 Design

The main design considerations revolve around the pond storage requirements and its impermeability, and the runoff conveyance, i.e. inlet/ overflow structure which also incorporates a silt-trap.

3.4.1 Storage requirements

Irrigation requires more volume of water than domestic or livestock uses. Therefore, a careful analysis of the water storage potential/capacity is required to evaluate the feasible scale of irrigation that can be sustained (MWI, 2015). In order to calculate the storage requirements of the pond reservoir, several key variables need to be taken into account, especially the runoff produced by the catchment area and the water requirements of the crops. In this manual, it is strictly recommended to also make reference to the comprehensive technical recommendations given by MWI (2015) in Chapter 8 “Hydrology and Sediment Analysis” and Chapter 14 “Pans and Lagoons” for the storage requirements, and MWI (2005) for the irrigation water demand. This information can be complemented with the contextualised training materials for Ethiopia, Kenya, Mozambique and Zimbabwe given as part of the AFRHINET advanced course on RWHI management which are accessible at **http://afrhinet.eu/materials.html**.

It usually takes a few rainfall events for a pond to be filled up in normal rainfall years even in small runoff catchments smaller than 4 ha (Ngigi and Oremo, 2015; Nissen-Petersen, 2015). Assuming that the catchment area generates sufficient runoff to fill up the pond reservoir, the storage capacity of the farm pond can be matched to the seasonal crop water requirements computed from the size of the drip irrigation system. For example, a 50 m^3 farm pond usually goes with a 230-L mini-tank drip irrigation system, which covers 250-300 m^2 of land. Crop water requirements can be assumed to be 230 L twice a day, which is equivalent to 46 m^3 for horticultural crops within a 100-day off-season growing period (MWI, 2005; MWI, 2015; Ngigi and Oremo, 2015). A minimum 90-day storage requirement responds to the need for an irrigator to be able to meet the irrigation demands for the entire duration of a dry season of 90 days (MWI, 2015). In addition, other domestic water uses should also be incorporated in the design to ensure sufficient water storage for off-season irrigation.

Once the required storage capacity is determined, the next step is to decide on the appropriate dimensions and orientation of the farm pond. Formula 1 and Figure 9 show how to compute the volume and some standardized dimensions. However, the sizes and dimensions of farm ponds are flexible and can be tailor-made to suit different landscapes, water demands and farmers’ preferences, and financial resources. Table 9 shows typical dimensions for different storage capacities of farm ponds.

The volume of a farm pond (m^3), which adopts the shape of an inverted trapezoid, is computed as follows:

$$V = (TL \times TW) + (BL \times BW) + 4\left[\frac{(TL+BL)}{2} \times \frac{(TW+BW)}{2}\right] \times \frac{h}{6}$$

Formula 1

> Where V is the volume of the pond (m^3), TL is the top length (m), TW is the top width (m), BL is the bottom length (m), BW is the bottom width (m) and H is the height (m).

3.4.2 Inlet conveyance mechanism

An inlet conveyance mechanism, which is shown in Figure 10, is a system comprised of the channels along the catchment area (e.g. road), the waterways towards the pond, the silt traps and the mitre drains. Surface runoff collects a lot of silt especially if the catchment is not well protected, e.g. drainage from conventional roads and foot paths. If the road has a convex shape, then it becomes easier to treat its conveyance channels on the sides by placing check structures and water breaks made of twigs to reduce siltation.

Siltation can be reduced in the conveyance channel through a combination of stone pitching and/or planting of indigenous grass and/or a tractor-tread design using stones or pegs of tree branches, as it is shown in Figure 11.

In addition, silt traps can minimise siltation and also act as a spillway. There are a number of designs and dimensions of silt-traps that have been tested and adopted in different places that mainly depend on the size of the pond, the nature of the catchment collecting the runoff and the soils present in the catchment area. The most common and most effective type is a double chamber silt trap. This type has two chambers (each of 60 cm x 60 cm x 60 cm) for sedimentation, where silt settles as the water enters into the farm pond. The silt trap acts as an inlet of the farm

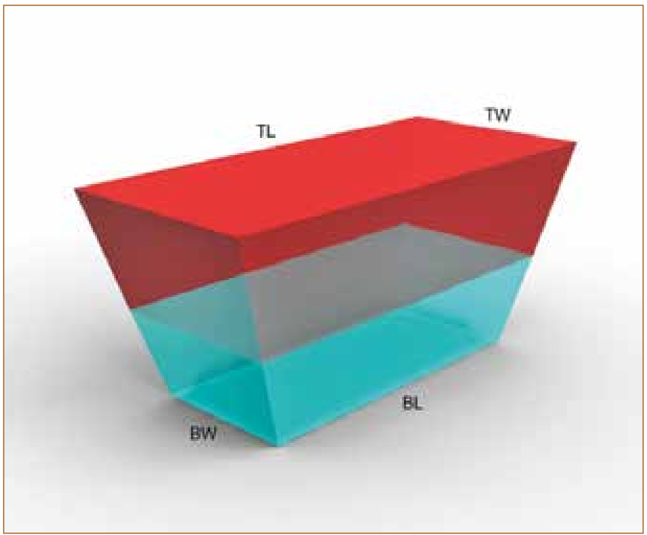


Figure 9: Parameters for farm pond volume computation.
Source: Pixiniti Studios.

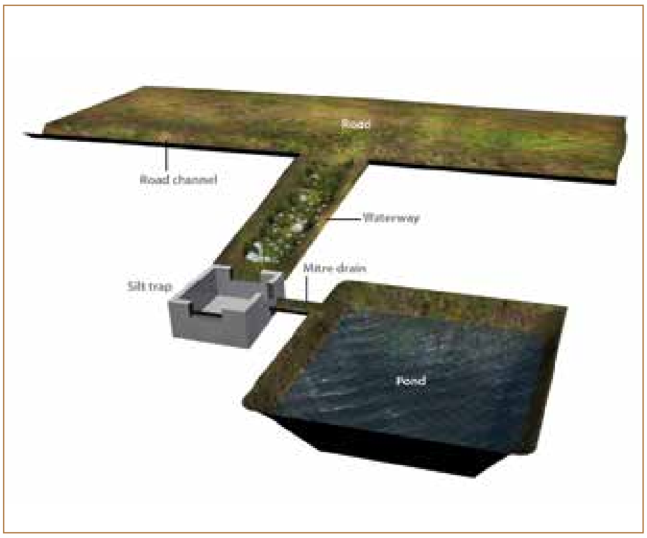


Figure 10: Runoff system from the catchment to storage.
Source: Pixiniti Studios.

Table 9: Typical dimensions for different storage capacities of farm ponds.
Source: Kenya Rainwater Association.

Top dimensions		Bottom dimensions		Depth (m)	Volume (m^3)
a (m)	b (m)	c (m)	d (m)		
8	6	4	2	2.00	**50**
8	6	6	2	2.25	**75**
10	6	8	2	2.25	**90**
12	7.5	8	3.5	2.25	**12**
14	8	8	4	2.25	**150**
14	8	10	4	2.5	**180**
15	8	11	4	2.5	**200**
15	10	11	6	2.5	**250**
16	11	12	6	2.5	**300**
16	12	12	8	2.5	**350**
16	14	12	10	2.50	**400**
16	16	12	12	2.50	**500**
18	16	14	12	2.75	**600**
20	16	16	12	2.75	**700**
20	18	16	14	2.75	**800**
20	20	16	16	2.75	**900**
22	20	18	16	2.75	**1,000**

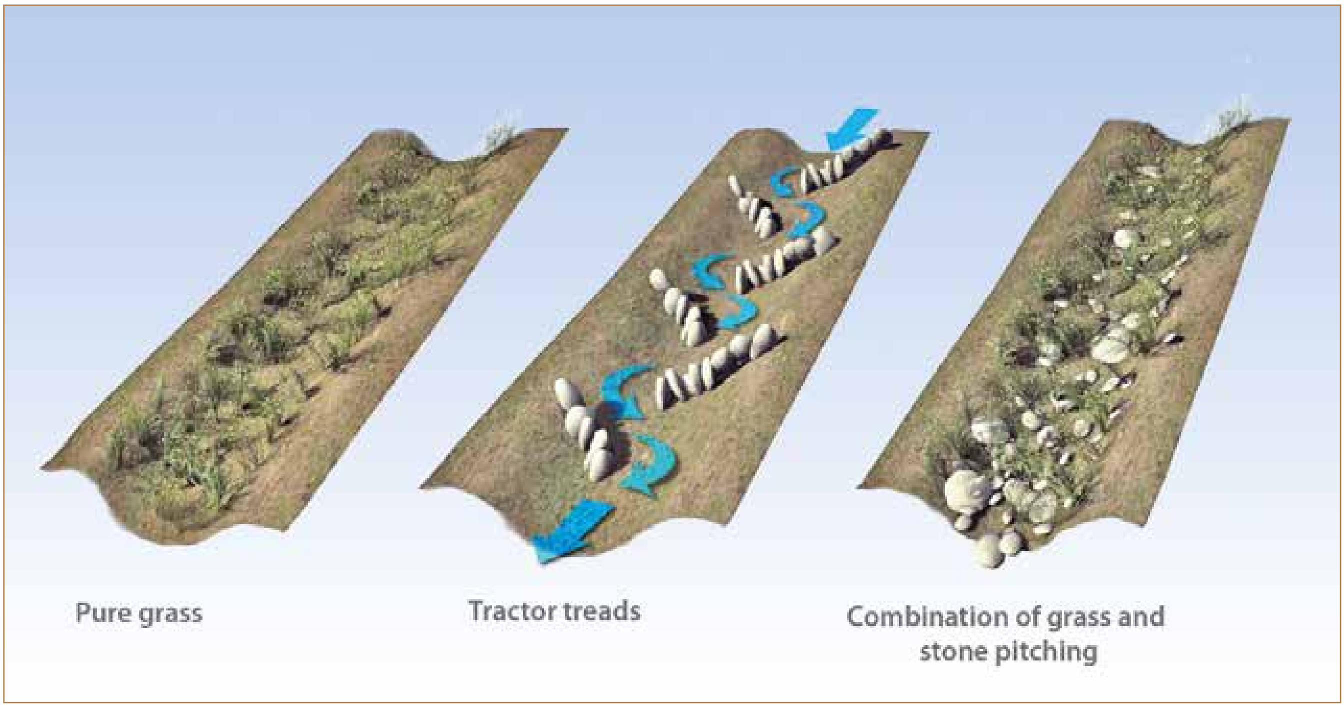


Figure 11: Type of treatments for channels and waterways.
Source: Pixiniti Studios.

pond as well as an overflow outlet. The two chambers are made of rubble masonry (e.g. bricks or dressed stones) and plastered for ease of maintenance. There are two inlets fitted with 10-cm PVC pipes coupled with screen filters in order to ensure that the runoff is well filtered and to prevent floating debris from entering the farm pond.

The location of the silt trap division box should be off-stream. The division box is an automated mechanism which minimises the silt content of the runoff entering the pond. When the pond is full, excess water flows back to the silt trap and flows out to downstream areas. It is important to construct an apron on the downstream side of the division box in order to avoid erosion at the outlet. The division box can be designed in a Y- or T-shape. Figure 12 is an example of a T-shape silt trap division box. For a Y-shaped division box, the downstream and pond channel take the shape of the upper part of the letter Y while the main inlet forms the lower tail of the letter Y. Further,

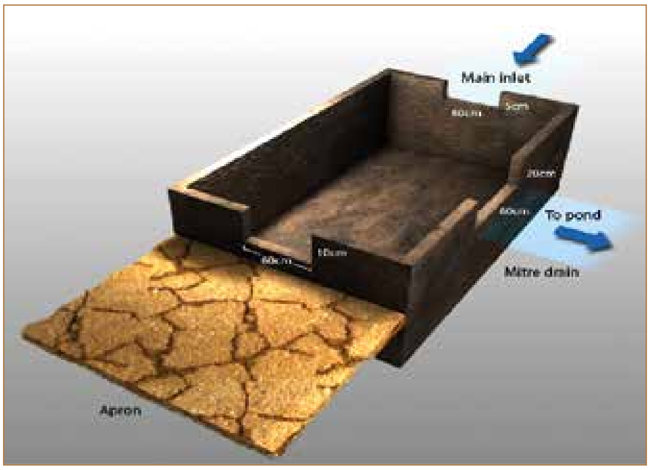


Figure 12: A silt trap division box.
Source: Pixiniti Studios.

the size of the division box is influenced by the size, soil type and vegetation cover of the catchment area, and the size of the pond. However, in rural areas where runoff is usually harvested from small roads and paths, a standard size of 1.4 m^3 volume with width of 1.2 m, length of 1.8 m and depth of 0.6 m would suffice. In addition, on the upstream side, the inlet for incoming runoff into the pond should have a depth of 5 cm and a length of 60 cm. The outlet from the division box to the pond should have a depth of 20 cm and length of 60 cm, while the outlet from the division box to downstream the farm pond should have a depth of 10 cm and a length of 60 cm.

3.5 Construction

The construction process is illustrated with a 50 m^3 farm pond. The top and bottom dimensions are 8 m x 6 m and 4 m x 2 m, respectively, while the depth is 2 m, with side slopes of 1:1 (45°). The construction process entails three main steps:

1. Layout and excavation of the pit.
2. Lining with 0.8 mm thick ultra-violet resistant (UVR) plastic sheet for seepage control.
3. Roofing with shade net (supported with either bow-shaped simple metallic structures for smaller capacities or flat meshed wire network), including anchoring masonry works and fencing.

3.5.1 Farm pond layout and excavation

This involves excavating the pit, which generally should have a trapezoidal shape in order to avoid the collapsing of the sides and to enhance the lining effect. After siting the farm pond, the top and bottom dimensions are marked out using strings or choke powder (Figure 13, left). Then excavation starts with the inner rectangular pit (4 m x 2 m), which is dug up to the required depth of 2 m, and then the outer rectangle (8 m x 6 m) is sloped to the required slope (1:1) in order to form the shape of the farm pond (Figure 13, right). The farm pond slopes are smoothened to allow the installation of the UVR plastic lining material to control seepage.

3.5.2 Lining of the farm pond

In areas with medium to high seepage, lining of the farm ponds has always been carried out immediately after excavation. The excavated farm pond is lined with a 0.8 mm thick UVR plastic sheet (dam liner) to prevent water losses through seepage. Other lining options such as concrete linings have also been implemented in other places. However, this is not recommended due to the costs and high labour involved. The dam liner is factory-made to fit the dimensions of the farm pond and includes 5% shrinkage allowance and 0.5-1.0 m overhang for anchoring to the ground. After fixing the dam liner perfectly into the pit, a one-course masonry layer (using brick, dressed or rubble stone) is constructed along the upper boundary (perimeter) of the farm pond. The masonry layer is laid about 20 cm from the top dimensions along a shallow ditch (10-20 cm deep) to hold the dam liner firmly to the ground and prevent side runoff from entering the reservoir (Figure 14). The short perimeter wall is provided with gaps at predetermined distances for fixing the anchors of the metallic roofing structure. For flat roofing, gaps are not necessary since the holding wires are fixed to the fencing poles along the outer side of the masonry layer. The masonry work is done by trained local artisans with labour and locally available construction materials provided by the community or beneficiaries.

3.5.3 Roofing the farm ponds

The farm pond is roofed with an 80% shading net (to allow entry of direct runoff), which is supported by a simple metallic roofing structure. The metallic roofing structure is prefabricated and transported to the site in easy-to-fix pieces. At the site, the roofing structure is assembled before being mounted along the masonry wall with semi-circular trusses being anchored by short metallic pieces, which are then fitted permanently into the ring wall gap by concrete (Figure 15, left).

The assembly of the roofing structure is easy and faster as all the members are fixed with bolts and nuts. After the assembled roofing structure is installed, the shade net is

Figure 13: Farm pond layout and excavation.
Photos: S. Ngigi.

Figure 14: Lining the farm pond including masonry layer for anchoring the dam liner.
Photos: S. Ngigi.


Figure 15: Farm pond roofing process.
Photos: S. Ngigi.

spread on the top and held tightly by binding wire along the bottom side, which prevents the net from being blown away by the wind (Figure 15, right). The net is properly balanced on top of the farm pond to maintain the uniformity. The metallic structure also has provisions for fixing binding/steel wires to prevent the net from sagging. For larger farm ponds, the flat net roofing incorporates fencing with chain-link to prevent damage by animals or reduce safety risks, i.e. drowning by either children or domestic animals. The shade net does not allow mosquito breeding, as it is shown in Figure 16.

Figure 16: Farm pond with flat net roof.
Photo: A. Oduor.

4. GROUNDWATER DAMS FOR OFF-SEASON SMALL-SCALE IRRIGATION

4.1 The technology

A groundwater dam is a macro-catchment rainwater harvesting storage technology which is built on sandy seasonal streams in rural arid and semi-arid areas (De Trincheria et al., 2016a). There are 2 main types of groundwater dams, subsurface dams and sand storage dams (Nilsson, 1988; Nissen-Petersen, 2006a). The main working principle of both structures is to obstruct the flow of shallow groundwater and store it in the riverbed, using alluvial sand sediments as a storage and supply mechanism (De Trincheria et al., 2015; 2016a,b).

Alluvial shallow groundwater from intermittent or ephemeral sandy streams is a traditional water source in arid and semi-arid areas (Botes et al., 2003; Dahan et al., 2007; McDonald et al., 2008; Morin et al., 2009; De Trincheria et al. 2015). If the original volume of alluvial shallow groundwater is sufficient to meet the needs of beneficiaries, it is not cost-efficient to implement a groundwater dam and efforts should be directed to improve water abstraction systems in order to enhance the access to water and its use for income-generating activities (De Trincheria et al., 2016a). However, if the natural accumulation of alluvial shallow groundwater in the riverbed is not sufficient to meet the water needs of the beneficiaries (Nissen-Petersen and De Trincheria, 2015; De Trincheria et al., 2016a), further development of the water yield and supply capacity of these rivers can be carried out by means of small-scale hydraulic retention structures across the sandy seasonal riverbed, i.e. groundwater dams (Wipplinger, 1958; Nilsson, 1988; Nissen-Petersen, 2006a, De Trincheria et al., 2016a).

Groundwater dams, especially sand storage dams, are widely distributed in arid and semi-arid areas of Kenya, from where have been replicated to other sub-Saharan African countries, and at a lower extent to south-eastern Asia and Latin America (De Trincheria et al., 2015). Figure 17 shows rural beneficiaries tapping into naturally available water on alluvial shallow groundwater reservoirs (top left), a subsurface dam, which lays underground the surface (top right), and two small-scale sand storage dams (bottom left and right).

4.2 Potential

The potential of groundwater dams revolves around 3 main factors:

1. Abundance of seasonal sandy streams in arid and semi-arid areas, as it is shown in Figure 19.

2. Seasonal sandy streams can naturally store and yield water during dry periods.

3. High cost-efficiency, as compared to other community-based rainwater harvesting technologies suitable for arid and semi-arid areas (Lasage and Verburg, 2015).

Factor 2 is worth of further consideration. In this regard, shallow groundwater from seasonal sandy riverbeds is not only a traditional water source well-known and accepted for rural communities but also a vital water source for these communities, especially during dry periods, poor rainfall years and droughts. Thus, when all other water sources have dried up, water can still be found in dry riverbeds (Nissen-Petersen, 2006a), as it is shown in Figure 18, which shows rural communities tapping into alluvial water beyond the peak of the dry season in rural eastern Kenya in 2012.

Figure 17: Different types of interventions on seasonal sandy rivers. Photos: J. de Trincheria.

The prevalence of alluvial shallow groundwater in seasonal sandy streams during dry periods is caused by shallow groundwater that gets naturally accumulated in specific sections of the streams during wet periods coupled with the capacity of sand sediments to store and yield water.

4.2.1 Storage of water in seasonal sandy streams

A specific section of a seasonal sandy stream has the capacity to naturally supply water during dry periods when a natural underground dike prevents shallow groundwater from seeping downstream through the sand (Nissen-Petersen, 2000; 2006a), as it is shown in Figure 20.

4.2.2 Water yield capacity of sand sediments

The specific yield of a sediment is the volume of water that a specific volume of sediments can yield after being saturated (Brassington, 2007). This yield is predominantly dependent on the grain-size (soil texture) and degree of sorting of the particles. However, the yield also depends on several other factors, among others: temperature, mineral

Figure 18: Seasonal sandy streams have the capacity to yield water during dry periods in arid and semi-arid areas. Photos: J. de Trincheria.

Figure 19: Large-scale seasonal streams (in blue) prevalence in Kenya. Source: Google Earth.

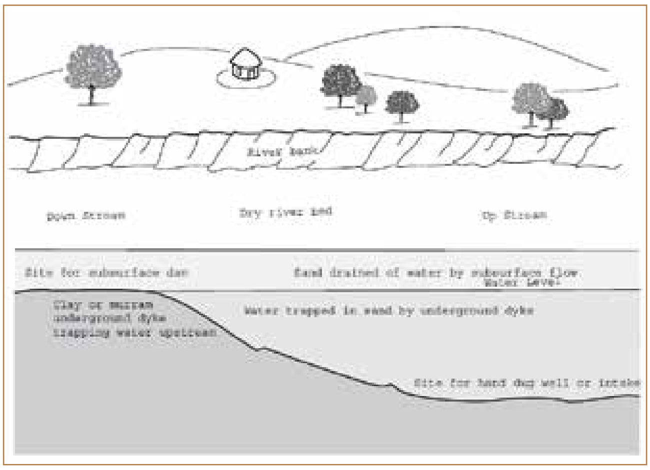


Figure 20: Storage of water in sandy streams due to natural underground dykes. Source: (Nissen-Petersen, 2000).

Table 10: Usual lab-based specific yield values for typical alluvial sediments. Source: (Brassington, 2007).

Material	Porosity (%)	Porosity (%)
Gravel (average coarse to fine)	31	24
Coarse sand	39	27
Medium sand	39	28
Fine sand	43	23
Silt	46	8
Clay	42	3

composition of the water and time of drainage (Brassington, 2007). Table 10 shows typical specific yield values for a range of alluvial sediments. From these values is obvious that water cannot be cost-effectively extracted from riverbeds containing large volumes of silty and/or clayey sediments. With the absence of real-life drainage measurements of alluvial sediments and under the precautionary principle, the real-life specific yield of medium and coarse sand sediments should be considered to be 20-25%. For small grain-sizes like silt and/or clay, the specific yield should be considered to be 0.5-3% (De Trincheria et al. 2015).

4.3 Advantages and disadvantages of groundwater dams

Table 11 shows a summary of key advantages and disadvantages of groundwater dams.

4.4 Key performance factors

The minimum optimal yield of a groundwater dam is 1,000 m^3/dry season (De Trincheria et al., 2017a,b). Key performance factors that are common to subsurface dams and sand storage dams basically refer to siting factors. These relate to the presence of a seasonal sandy stream, the existence of an impermeable bedrock at a feasible depth (3-5 m), a riverbed width not higher than 25 m to 50 m, and the presence of a catchment area that can produce medium to coarse sand sediments.

4.5 Subsurface dams

4.5.1 Key working principles

A subsurface dam 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 foundations of the weir must always be built on the underground dyke closest to the surface of the riverbed and reach the impermeable layer in order to avoid seepage (Nissen-Petersen, 2013) (Figure 21).

Table 11: Key advantages and disadvantages of groundwater dams.

Advantages	Disadvantages
Strategic water supply: Large volumes of water during dry periods, dry spells and droughts, when other available water sources do not usually yield water (Aerts et al., 2007; Ertsen et al., 2005, 2006; Lasage et al., 2008).	**High site-specificity:** Groundwater dams can only be applied cost-effectively if highly specific hydrogeological conditions area at hand (De Trincheria et al., 2015).
Income-generation potential: Support of vital activities during dry periods: domestic, livestock, agroforestry and horticulture. This is key for a sustainable income and livelihood in these areas (Hut et al., 2008; Lasage et al., 2008).	**High capital investment costs:** Usual construction costs from EUR 1,000 to EUR 30,000 (average costs around 8,000 EUR) cannot be afforded by local communities (Lasage and Verburg, 2015).
High cost-efficiency: High volumes of water at low costs over a significant lifespan taking into account their capital investment costs, and compared to other community-based RWH technologies (Lasage and Verburg, 2015).	**High external dependency:** Local communities cannot implement it without external aid because they do not have the technical capacity and knowledge for the siting and construction. Also because the construction is labour-intensive, and therefore, local communities do not have the time to build them (De Trincheria et al., 2016a).
Robustness to evaporation: Evaporation losses are negligible below 0.6 m-1 m depth of sand (Wipplinger, 1958; Helweg and Smith, 1978).	**Low self-replication:** Few examples of groundwater dams have spontaneously been replicated (De Trincheria et al., 2016a).
Robustness to siltation: The progressive loss of storage capacity over time is minimal in well-designed groundwater dams, as compared to surface reservoirs (Wipplinger, 1958). For sand storage dams, only if the spillway is built by stages of reduced height (De Trincheria et al., 2015, 2016a,b, 2017a).	**Limited usability:** Only riparian communities can cost-effectively benefit from groundwater dams. Communities not living close to the stream (1 Km) cannot benefit from income-generating activities, especially small-scale irrigation (De Trincheria et al., 2016a).
Increase of shallow groundwater levels: Caused by the retention of the subsurface flow of shallow groundwater (Borst and de Haas, 2006). This is caused by the foundations of the groundwater dam (De Trincheria et al., 2016a).	**Conveyance requirements:** Scalability and impacts strongly depend on conveying the water from the reservoir by means of manual and/or mechanical pumping and delivery systems (Hussey, 2007; De Trincheria et al., 2016b).
Reduction of erosion: Well-designed sand storage dams have the potential to reduce the erosive action of floods and increase the retention and infiltration of runoff, mainly due to the reduction of the gradient of the original riverbed (De Trincheria et al., 2015; 2016b).	**Weak link with income-generating activities:** Little use of the water for irrigated agriculture and other income-generating activities (De Trincheria et al., 2016a).
Riverbed reclamation potential: No land is occupied as for surface reservoirs. The land above the stored water can be used for other purposes (Nilsson, 1988).	
Robustness to cross-contamination: Water contamination is reduced because the sand acts as a barrier (Nilsson, 1988; Nissen-Petersen, 2006a).	
Robustness to mosquito breeding: As water is stored in the sand, there is no surface stagnant water, so breeding of mosquitoes is minimised (Nilsson, 1988; Nissen-Petersen, 2006a).	
Reduction of microbial contamination: Filtration of water through the sand voids reduces the occurrence of microbial contamination (Avis, 2016).	
High water quality: The quality of the stored rainwater is high and readily available for any use, as compared to surface reservoirs (Avis, 2016).	
Low downstream impacts: Runoff is not severely affected because the flow of water is not blocked (Nissen-Petersen, 2006a).	
Acceptability: They are socially acceptable as they are based on traditional sources of water.	

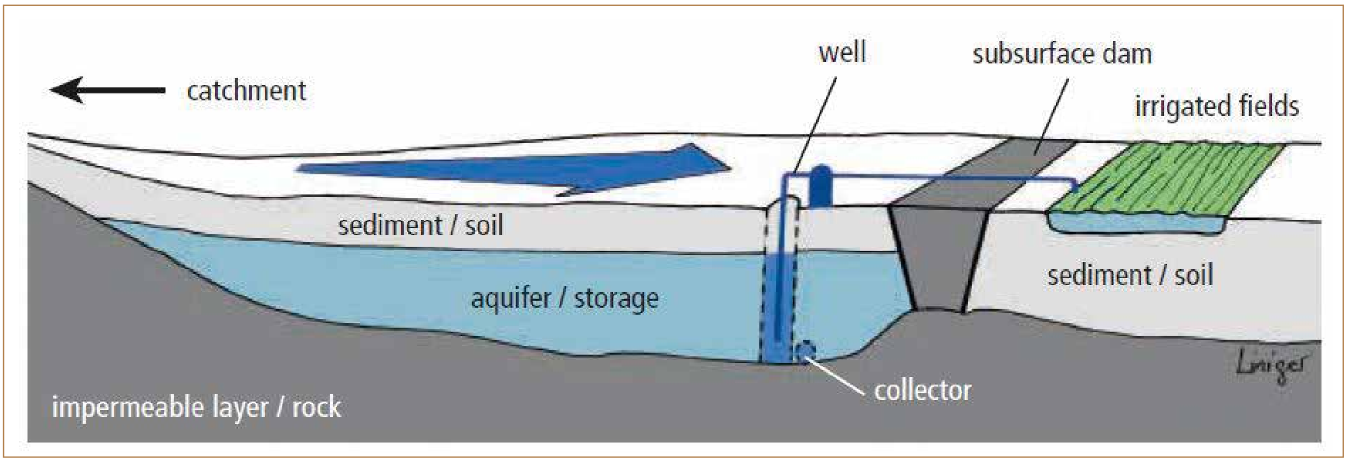


Figure 21: A diagram of a subsurface dam across a seasonal sandy stream. Source: (Studer and Liniger, 2013).

A subsurface dam is designed to increase the water yield of a sandy seasonal stream by blocking the shallow groundwater flow, thereby, creating a shallow groundwater reservoir, as it is shown in Figure 22.

4.5.2 Strengths and weaknesses

The strengths of subsurface dams revolve around their underground position, i.e. they do not block the surface runoff of the riverbed. In fact, Nissen-Petersen (2013) and De Trincheria et al. (2015) state that subsurface dams are the most cost-efficient type of groundwater dam due to the following factors:

1. Subsurface dams are not vulnerable to siltation because the weir does not block the runoff.

2. Subsurface dams are not vulnerable to the erosive action of floods due to their underground position, which cause high lifespans and robustness to floods.

3. As they do not have to resist the hydraulic pressure of the runoff, they do not need reinforcement and can be built of clayey soil, which minimises the construction costs and the technical complexity of the structure.

4. No maintenance and operation activities are required.

5. They do not require high riverbanks to be built.

6. High cost-efficiency potential: USD 0.2-0.3/m^3 (Nissen-Petersen, 2000).

To be cost-efficient and produce a tangible impact, a subsurface dam will always require natural deep layers of sand sediments in the riverbed. Therefore, subsurface dams are not indicated for sites which present shallow sand depths, especially at the upper head of the catchment area. Further, a major weakness of this type of groundwater dam may be the fact that the structure is invisible to the eye. This may actually make some donors and practitioners reluctant to implement it because it is difficult to prove that funds have been invested adequately. Further, even for local communitiesis difficult to relate to the structure because they simply do not see it. This may be one key factor influencing the extremely low adoption of this type of groundwater dam. Table 12 shows the constructions costs of a subsurface dam.

Figure 22: The increase of the shallow groundwater reservoir caused by a subsurface dam. Source: (Nissen-Petersen, 2013).

Table 12: Construction costs of a subsurface dam. The costs include hydrogeological survey, design permits, materials and labour and 15% indirect costs. Source: (Nissen-Petersen, 2013).

Dimensions (length x height)	Construction material	USD (2013)
24 m x 2.1 m	Clayey soil from a nearby riverbank	1,777
24 m x 2.1 m	Dam liner (Geomembrane)	2,188
24 m x 2.1 m	Rubble stone masonry	8,762
24 m x 2.1 m	Reinforced concrete in timber shuttering	21,105

4.6 Sand storage dams

4.6.1 Key working principles

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 main 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 Figure 23. 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.

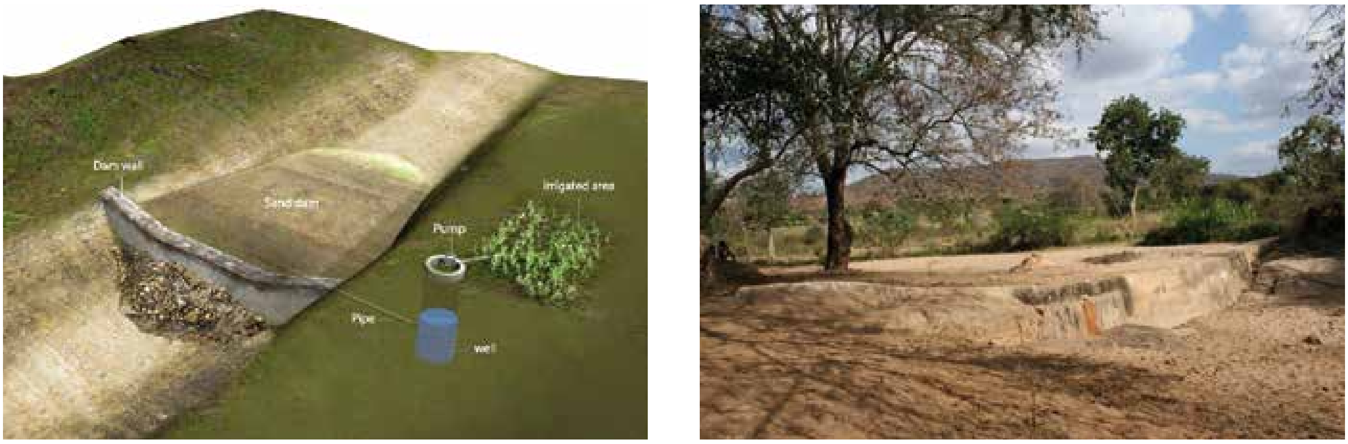


Figure 23: The increase in sand sediments on the original riverbed caused by the construction of a sand storage dam: a diagram (left) and a real-life example (right). Source: Pixiniti Studios. Photo: J. de Trincheria.

The main key working principle of a sand storage dam is to maximise the accumulation of suitable grain-size sand sediments behind the dam wall. As sand sediments of high permeability and specific yield are predominantly carried out as bedload in the runoff, this implies that a sand storage dam needs to be specifically designed to exclusively accumulate the bedload flux (De Trincheria et al., 2016b). Further, as fine sand sediments and finer grain-size particles (clayey and silty sediments) of low permeability and specific yield are predominantly transported as part of the suspended load, this implies that sand storage dams should minimise the accumulation of the suspended load (De Trincheria et al., 2016b). The universal dynamics of sediment transport are shown in Figure 24.

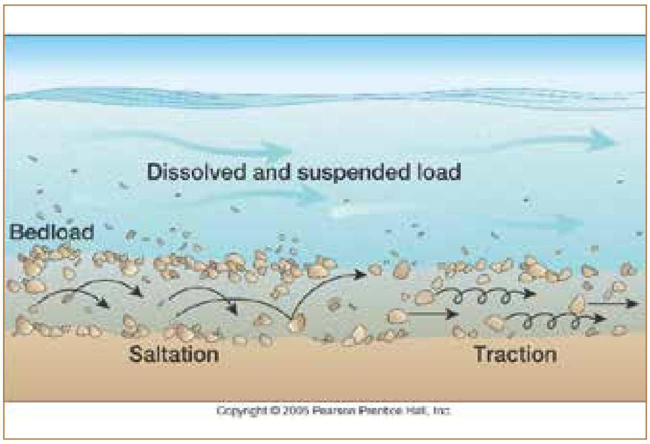


Figure 24: Classical view on sediment transport in fluvial systems. Source: Pearson Prentice Hall.

4.6.2 Strengths and weaknesses

The real-life performance and cost-efficiency of a sand storage dam can be severely reduced by siltation, seepage and evaporation problems (Baurne, 1984; Nissen-Petersen, 2000, 2006a, 2011, 2013; De Trincheria et al., 2015, 2016b, 2017a). To avoid siltation and seepage requires highly specialised technical know-how and an adequate understanding of the hydrogeology and sediment transport dynamics of the catchment area. However, to understand these dynamics is complex, time-consuming and expensive because of the multi-dimensional heterogeneity and high inter- and intra-annual variability of these factors (Wheater and Al-Weshah, 2002; McDonald et al., 2008; De Trincheria et al., 2015). Currently, these biophysical factors and technical constraints are not adequately understood (De Trincheria et al., 2015). Table 13 shows an overview of key performance factors affecting the cost-efficiency of sand storage dams.

4.6.3 A focus on siltation

Sand storage dams are highly vulnerable to siltation. Estimates suggest that siltation may be affecting between 40-60% of sand storage dams implemented in arid and semi-arid areas in general, and Kenya in particular (De Trincheria et al., 2016b, 2017a). Siltation is caused by the accumulation of large volumes of low-permeability fine grain-size sediments in the reservoir (Fan and Morris, 1992; Brandt, 1999; Stephens, 2010) and dramatically reduces the performance, cost-efficiency, and associated multi-dimensional benefits of sand storage dams (Wipplinger, 1958; Nissen-Petersen, 2011; De Trincheria et al., 2015, 2016b, 2017a). In addition, silted-up reservoirs present high vulnerability to evaporation (Wipplinger, 1958; Hellwig, 1973) and are unable to meet local community needs during dry periods (De Trincheria et al., 2015, 2016b, 2017a). Figure 25 shows a sand storage dam affected by siltation.

De Trincheria et al. (2016b) carried out an in-depth analysis of the universal hydraulic and hydrogeological principles that explain the vulnerability to siltation of sand storage dams. Basically, the vulnerability is caused because the

Table 13: Key performance factors affecting the cost-efficiency of sand storage dams. Source: (De Trincheria et al., 2015).

Performance factor	Description and causes
Siting: Catchment areas producing none or low volumes of coarse sandy alluvium sediments	Hydrogeological characteristics of the catchment area and the sediments transported by the runoff. Inherent high variability of rainfall, runoff and sediment transport during the filling up of the reservoir. Specific position of the sand dam in the catchment area, i.e. close to the head of the valley.
Siting: Width of the riverbed	Nissen-Petersen (2006a) recommended avoiding riverbeds wider than 25 m because the cost-efficiency of the structure may be undermined by the high construction costs required to assure robustness to flood damage.
Siting: Throwback	In sand dams sited on steep slopes, the throwback will necessarily be lower.
Siting: Upstream sand storage dams	The implementation of an upstream sand dam at a distance cutting the throwback of a downstream sand dam before it is filled up of sand will limit the effective accumulation of alluvium sediments and/or may increase the siltation for the downstream sand dam.
Siting: Catchment areas producing large volumes of fine sandy alluvium sediments	Low sorting degree levels of the sediments accumulated in the reservoirs may reduce the inherent low real-life specific yield of fine sand (Brassington, 2007).
Siting: Catchment areas producing large volumes of silty and / or clayey alluvium sediments	Caused by the hydrogeological characteristics of the catchment area and / or as side effect of one-stage high spillways. This is a clear indicative that the performance and cost-efficiency of the sand storage dam will be poor. Low yield is caused by the low permeability of silty and clayey sediments. Also, by clogging of sand with silt/clay (Helweg and Smith, 1978) or the formation of a silt layer below the mobile upper part of the bed (Wipplinger, 1958).
Siting: Evaporation losses	Hellwig (1973) and Wipplinger (1958) proved that evaporation is negligible from 0.6-1.0 m for coarse sand. Accumulation of predominantly fine grain-size sediments may increase the evaporation depth (Helweg and Smith, 1978). Shallow sand reservoirs may not only have limited storage and yield capacity but a higher vulnerability to evaporation.
Siting and design: Seepage losses	Systematic seepage of the water stored in the reservoir through boulders, fractured sedimentary rocks and permeable layer of sediments (Baurne, 1984; Nissen-Petersen, 2000, 2006a; Forzieri et al. 2008). Also caused because the foundations of the sand storage dam are on rock outcrops instead of being keyed to the impermeable layer (Nissen-Petersen and De Trincheria, 2015).
Design: Variability of rainfall, runoff and sediment transport	There is an inherent variability of rainfall, runoff and sediment transport, specifically, the bedload transport and the volume of sand sediments transported in the runoff at inter- and intra-annual level. This implies not only that the height of the bedload layer varies but also that there are runoff events which do not transport sand.
Design: One-stage spillways	The height of the spillway reduces the flow velocity, the energy available for transport and the height of the bedload layer, and therefore, increase the accumulation of silty and clayey materials. One-stage spillways produce graded-bedded reservoirs of low permeability in a wide range of conditions. The thickness of the clayey and/or silty sediments accumulated decreases the scouring capacity of the runoff. Independently of the actual distribution of different grain-size sediments along the thickness of the reservoir, the upper layer of the reservoir will consist of the coarsest alluvium sediments that the runoff may have.

Figure 25: A sand storage dam severely affected by siltation (left) and universal dynamics of fluvial sediment transport (right). Photo: J. de Trincheria.

bedload transport is highly variable and often inexistent inter- and intra-annually in arid and semi-arid areas, and corresponds to a minority fraction of the total sediment yield. In addition, the height of the spillway increases the deposition of fine grain-size sediments in the reservoir. These hydrogeological arguments are also true for sites with the geological potential to produce coarse sand sediments (Alexandrov et al., 2003, 2009; Lucia et al., 2013).

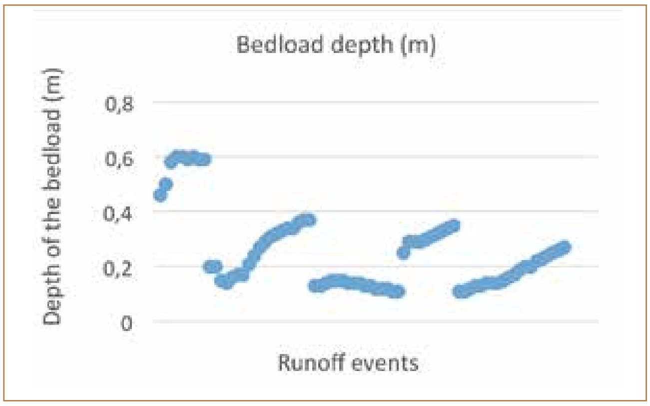


Figure 26: 5 runoff events (each of the group of blue dots) in 1991 for an ephemeral stream in the Negev Dessert.
Source: Adapted from Reid et al. (1995).

Figure 26 shows an example of the bedload variability in arid and semi-arid areas by showcasing 5 runoff events in 1991 for an ephemeral stream in the Negev Desert (Reid et al., 1995). It can be observed that the maximum and minimum bedload height was 0.6 m and 0.1 m. Also, that the bedload is highly variable not only between different runoff events but also during the same runoff event. From this graph, it can be inferred that a spillway of 1 m would have accumulated 40% of silty and clayey materials on the surface if we take the first runoff event, which was the most intense. With all the other runoff events, the spillway would have accumulated between 60%-90% of the suspended load.

Nissen-Petersen (2011) and De Trincheria et al. (2015, 2016b, 2017a) argued that the major cause for siltation in sand storage dams is associated to the design of the spillway. Currently, the final spillway height of most sand storage dams, which is usually between 1-5 m, is built in one stage. Due to the stage height and the high inter- and intra-annual variability of the bedload transport in arid and semi-arid areas, the one-stage spillway design has an inherent high vulnerability to accumulate large volumes of fine grain-size sediments which are transported as part of the suspended load in the runoff. Thereby, inducing the siltation of the reservoir. The universal replication of this design across arid and semi-arid areas implies that the large number of silted-up sand storage dams in Kenya may be highly representative of other arid and semi-arid areas.

Alternative spillway designs that minimise siltation have been in existence at least since the 1950s (Wipplinger, 1958; Baurne, 1984; Nilsson, 1988; Nissen-Petersen, 2000, 2006a, 2011; Ochieng et al., 2008; De Trincheria et al., 2015, 2016b). Among these, the design that shows the highest potential to systematically minimise siltation, and therefore, assure universal optimal levels of performance and cost-efficiency is to design and build the spillway by stages of reduced height. The main key advantages of a multi-stage spillway construction process is the maximisation of the performance and cost-efficiency in all type of rainfall, runoff and sediment transport events. The key disadvantage, which applies only to intermittent streams, is that the construction time is 3-5 years for conventional final spillway heights (De Trincheria et al., 2016b).

Figure 27: A sand storage dam with severe problems of seepage.
Photo: J. de Trincheria.

4.6.4 A focus on seepage

The main causes leading to seepage (Figure 27) are as it follows (Nissen-Petersen and De Trincheria, 2015):

1. Building the wall on boulders.

2. Permeable bedrocks.

3. Predominance of boulders on the riverbed.

4. Fractured sedimentary rocks on the riverbed.

However, seepage can be beneficial for boreholes and/or deep/shallow hand-dug wells on the riverbanks.

4.7 Practical recommendations for groundwater dams

There is comprehensive and exhaustive information and know-how on how to site, design and build cost-efficient groundwater dams on the technical guidelines produced by MWI (2015) and Nissen-Petersen (2000, 2006a, 2013). Therefore, it is recommended to use these guidelines in order to implement a groundwater dam. In order to not duplicate already available information, the practical recommendations of these training materials focus on specific aspects of the siting, design and construction of groundwater dams which need special attention and/or are not covered in the guidelines currently available.

4.7.1 Tapping into the natural capacity of alluvial reservoirs

Prior to the implementation of a groundwater dam, it is always necessary to take into account the following key recommendations:

1. If the specific section of the 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 improve the water abstraction systems connected to the riverbed and/or improving the water access for local communities, especially, the link with small-scale irrigation. Thus,

Table 14: Structures for tapping into the natural water yield capacity of dry riverbeds. Source: (Nissen-Petersen, 2006a).

Performance factor	Description and causes
Waterholes	Shallow waterholes are the most popular extraction method for pastoralists and agro-pastoralists, because the lifting height is low and the investment consists only of a shovel, a discarded tin and either a few jerry cans for domestic water or a hollow tree trunk for watering livestock. Waterholes can be used for off-season small-scale irrigation purposes with only the investment of the water pump and irrigation application system, if any.
Shallow hand-dug wells in riverbeds or riverbanks	A hand-dug well is a well dug manually, where the only piece of machinery eventually used is a water pump to enable the workers to do their job in relatively dry conditions. It is a potentially dangerous undertaking, especially when the hole in the ground has to go deeper than 5 m. Sometimes it can go as deep as 20 m or even more. Nevertheless, wells should always be sunk in the inner bends of riverbeds where sand deposited by former water courses provides natural infiltration and recharge of water to the wells. Naturally, wells and intakes should be sunk where the water-saturated sand is deepest for the purpose of extracting a maximum of water. Hand-dug wells sunk in the riverbanks are protected from damage by floodwater but are often abandoned by the water users due to the tiresome work of lifting water from the depth of a well instead of scooping it up from the wadi. To enhance access to water, a shallow well fitted with a hand pump is constructed along the river bank upstream of the dam, which improves water abstraction and quality – reduce contamination
Outlet pipe with tap	An outlet can be installed as a perforated pipe at the deepest part of the reservoir just above the impermeable layer. The pipe should be covered fully with filter material and geomembrane to prevent entry of sand and silt. Disadvantages are that the maintenance is complicated and it is an expensive option.
Intakes in riverbanks	River-intakes are similar to hand-dug wells except for an infiltration pipe that drains water from the riverbed into a well sunk in a riverbank. Intakes are only constructed where there is insufficient inflow or recharge of water to a well sunk in a riverbed.

development agencies should give more attention to low-cost water projects incorporating upgraded waterholes and hand-dug wells, among others. Siting, design and construction recommendations on these type of structures are comprehensively given by MWI (2015) and Nissen-Petersen (2000, 2006a). An overview of these water abstraction options is shown in Table 14.

2. If the specific section of the sandy seasonal stream cannot yield enough water to meet local community needs, a subsurface dam then needs to be first considered always before than a sand storage dam because of higher cost-efficiency, simplicity and robustness to erosion and siltation.

3. If the yield produced by the seasonal sandy stream after considering a subsurface dam cannot yield enough water to meet local community needs, then a sand storage dam is the most cost-efficient groundwater option to meet the needs of the beneficiaries.

4.7.2 Siting

If the implementation of a groundwater dam is required, siting is a vital step to carry out this process cost-efficiently. Thus, key siting steps are as it follows:

1. Identify suitable catchments with the capacity to produce large volumes of sand sediments.

2. Identify suitable sandy seasonal riverbeds in suitable catchment areas.
3. Locate underground reservoirs and dykes on suitable riverbeds.

4. Evaluate sand storage capacity, water yield, supply and cost-efficiency, and water needs of beneficiaries.

5. Select the most cost-efficient, simple and robust intervention.

4.7.2.1 Identifying suitable catchments and/or riverbeds

The first 2 siting steps, which require a macro-scale assessment, can be carried out using relatively sophisticated methods by combining remote sensing and GIS-based data and tools. A scientific-based method to do this has been proposed by Forzieri et al. (2008). However, these methods require specialised technical skills, the availability of adequate data, and software tools.

Alternatively, a simpler technique for siting steps 1-2 is studying already available satellite images and other data sets that can be found online using Google Earth Pro. Thus, in order to identify suitable catchment areas and riverbeds, the following recommendations need to be taken into account. Figure 28 shows suitable and unsuitable catchment areas.

a) Hilly and rocky watersheds and gullies originating from stony hills have the potential to produce large volumes of coarse sand from where up to 25-20% of water can be extracted.
b) Watersheds of flat farm land have the potential to produce large volumes of fine sand coupled with clayey and silty materials, from where 0.5%-5% can be extracted. This is independently of the fact, that in many cases, these catchment areas have also the capacity to produce low volumes of medium and coarse sand sediments.

c) Seasonal sandy streams with abundance of rock outcrops on the surface of the riverbed and/or across the thickness of the riverbed, have a high potential to seepage water (Nissen-Petersen, 2013).

Further, in order to identify at the micro-scale level the best suitable implementation sections on suitable seasonal sandy streams using Google Earth Pro, the following key information needs to be taken into account:

a) Potential places for sinking wells and intakes in dry riverbeds are basically identified by the presence of waterholes with water during dry periods and water-indicating tress (Nissen-Petersen, 2013).

Figure 28: A suitable (left) and unsuitable (right) catchment.
Photos: E. Nissen-Peteresen.

b) Groundwater dams should be located downstream of wells where there are no waterholes or water-indicating trees.

4.7.2.2 Identifying cost-efficient construction sites

Siting steps 3-5 should be carried out always after a 1-day field survey (Nissen-Petersen, 2006a; De Trincheria et al. 2015, 2016b). The main objective of the field survey is to optimise performance, cost-efficiency and benefit to local communities by means of:

a) Tapping into the natural capacity of the riverbed in a cost-efficient manner.

b) Disregarding sites with low potential before the implementation takes place (seepage, evaporation, and siltation).

c) Selection of best sites: natural deep layers of sand-sediments and/or alluvial aquifers laterally extending.

The first step of the field survey is to identify suitable specific sections of the riverbed. According to Nissen-Petersen (2013) and Nissen-Petersen and De Trincheria (2015), this can be carried out with quick and simple yet accurate methods by taking into account the following factors:

a) Location and types of water indicating trees.

b) Location of waterholes and hand-dug wells.

c) Location and types of rocks and boulders.

d) Coarseness of sand sediments.

e) No calcrete.

f) Avoid building in bends of the river.

g) Finding suitable places to build the dam is harder when the river is wider.

h) In general, the topographical gradient of the construction site should be 0.2%-4% but in extreme cases slopes of 10%-16% can be used (Nilsson, 1988).

i) Drawing a sketch of the potential sections identified.

Once suitable specific sections have been identified, it is necessary to locate underground reservoirs and dykes using a combination of 3 quick and simple methods:

1. Waterholes with water during dry periods.

2. Natural indicators, especially, water-indicating trees.

3. 1-day probing of the width and depth of sand sediments in the riverbed.

A detailed overview of these methods is as it follows:

Waterholes in the riverbed during the dry season
Waterholes in riverbeds and tall trees on riverbanks indicate shallow groundwater suitable for sinking hand-dug wells in the inner curve of riverbanks, as it is shown in Figure 29. The yield of water from a well can be increased by a subsurface dam or a sand dam built on an underground dyke downstream of the well where there are no trees or waterholes. Also, the time length and volume of water used for the beneficiaries give a first indication of the yield capacity of the site.

Natural indicators of shallow groundwater
Woodhouse (1991) found that the most successful natural indicator of good-quality groundwater at shallow depth was Acacia robusta. Thus, where this tree is supported by topographical indicators, groundwater can be obtained at depths of less than 10 m. In addition, Acacia gerrardii, Acacia xanthophloea and Fikus sur are all useful indicators of shallow groundwater and their presence in conjunction with A. robusta confirms a good site. Also, the absence of termite mounds with Sterculia rhynch and Acaccia mellifera are a good indicator of shallow groundwater. Finally, the presence of tress with green cover during the dry season is a good indicator as well.

Figure 29: A waterhole identified by means of Google Earth.
Source: (Nissen-Petersen, 2013).

Geophysical survey at the site level

To measure depth and width of sand sediments of the specific section (500 m - 1,000 m) of the riverbed where the groundwater dam is to be built is required in order to tap into the natural capacity of the riverbed in a cost-efficient manner. This means to be able to build the spillway at the shallowest point where there is an underground dyke and to place the spillway downstream of the maximum depth of sand. Also, the evaluation allows to disregard specific sites with low potential before the implementation takes place (seepage, evaporation, siltation), and therefore, to optimise performance, cost-efficiency and benefit to local communities. In addition, with the data collected, the potential water yield and supply capacity can be estimated, and therefore, the groundwater dam can be designed in the most cost-efficient manner. The height of the stages and potential construction costs can also be obtained as a result of the on-the-ground evaluation.

The simplest method to survey the riverbed is to hammer iron rods of 2 m and 4 m (14-16 mm) into the ground along 500 m or 1,000 m at sub-sections of intervals of 20 m or 10 m (Figure 30). At each probing point, the depth of sand and water is measured at least once in the middle of the sub-section. There is also the need to record other key variables, i.e. gradient of the riverbed, texture of sand, floor under the sand, height of the riverbanks, items seen on the banks, and the specific yield of the alluvial sediments.

The objective of the probing is to be able to develop a longitudinal profile and plan, as it is shown in Figure 31.

Figure 30: A probing procedure.
Source: (Nissen-Petersen, 2013).

The analysis of the data collected serves to select the most cost-efficient, simple and robust intervention on the riverbed. The objective is to gain free storage capacity and reduce costs by building on underground dykes. In addition, the probing allows conducting a hydrological evaluation of the reservoir. This is meant to evaluate if the water yield of the reservoir can meet the water needs of the benefi-

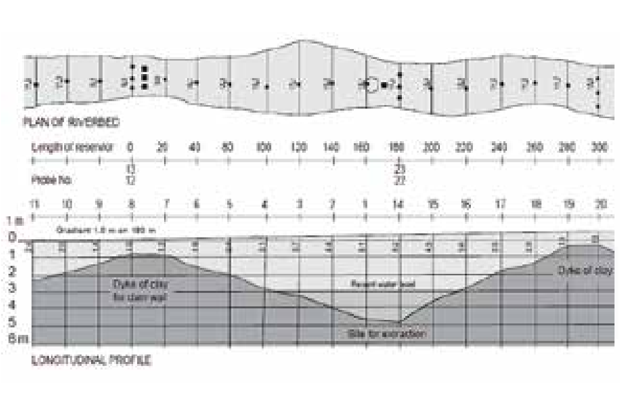


Figure 31: Longitudinal and profile plan of a seasonal sandy stream.
Source: (Nissen-Petersen, 2000).

ciaries, and therefore, to identify the most cost-efficient option to implement, i.e. waterholes and/or hand-dug wells, pumping and conveyance systems, subsurface dams or sand storage dams.

A simple but slightly inaccurate method method to estimate sand storage capacity and water yield was developed by Hudson (1975) and proposed by Nissen-Petersen (2006a) to estimate the yield of a groundwater dam. Thus, the extractable volume of water from a sand reservoir can be estimated using Formula 2.

$$C = \frac{L \times T \times D}{6} \quad \text{Formula 2}$$

> Where C is the total sand storage capacity (m^3), L is the maximum length of sand sediments in the reservoir (m), T is the maximum throwback and D is the maximum depth of sand sediments. This calculation assumes that the basin of the reservoir is an inverted pyramid (Hudson, 1975).

The throwback is the length of influence of the groundwater dam and it is found on the point where the final height of the spillway intersects the depth of sand sediments (subsurface dam) or the slope of the riverbed (sand storage dam) (De Trincheria et al., 2017a,b).

The water yield of the sand storage dam is found by multiplying the sand storage capacity (C) and the specific yield of sand (n). The specific yield of sand is given by Formula 3:

$$n = Y_S / V_S \quad \text{Formula 3}$$

> Where Y_S is the volume of drained water (L) and V_S is the volume of sand (L)

Table 15: Performance analysis.
Source: (De Trincheria et al., 2017a,b).

Variable	Formula	Description and causes
Storage capacity of each section	$C_P = K * D * W * T$	Where C_P is the reservoir capacity (m^3), K is a constant to reflect the geometrical shape of a reservoir (i.e. K=1 for riverbeds at upper levels of the catchment area, K=1.6 for riverbeds at lower levels), T is the length of each probing section at intervals of 10 m or 20 m (m), and D and W are the depth and width of each section (m), respectively.
Evaporation losses	$D_E=D-[0.6\text{-}1.0]$ (m) $C_{PE}= K * D_E * W * T$ (m^3)	To take into account evaporation losses, an evaporation depth of 0.6 m (Hellwig, 1973) to 1.0 m (Wipplinger, 1958) should be taken into account.
Total sand storage capacity	$C_T = \sum C_{1 \text{ to } n}$ $C_T= C_{P1} + C_{P2} + C_{P3} + \dots + C_{Pn}$	Where C_T is the total reservoir capacity (m^3), C_P is the reservoir capacity of each probing point.
Water yield of a sand dam	$Y_A = C_T \times n \times R$	Y_A indicates the capacity of the reservoirs to yield water per year taking into account the volume of sand accumulated and the associated specific yield of the sand sediments. Where Y_A is the annual water yield of the sand reservoir (m^3/year) and R is a constant which reflects the number of rainy seasons in the study area.
Seepage losses	$Y_S= Y \times Sp$	Where Y_S is the yield after accounting seepage (m^3) and Sp is a conservative constant which aims to reflect minimum potential seepage losses (%). Sp= 10% (Stephens, 2010)
Water supply	$S_S= Y_D / Co_D$	Where S_S is the total number of households supplied by the groundwater dam during one dry season (households), Y_D is the effective water yield of the sand dam during that specific dry season (m^3) and Co_D the water needs per household during that specific dry season (m^3). Co_D is given by $Co_D=Co_H \times L_D$ Where Co_H is the total consumption of one household per day (m^3/day) and L_D is the length of the dry season (days).

For example:

25 % of water can be extracted from 5,000 m^3 sand = 1,250 m^3 water.

5 % of water can be extracted from 5,000 m^3 sand = 250 m^3 water.

A more accurate method to estimate the sand storage capacity, yearly water yield, supply capacity and cost-efficiency has been developed by De Trincheria et al. (2017a,b). This evaluation can be carried out during and after the construction in order to monitor and evaluate the performance and cost-efficiency. Table 15 and 16 show an overview of the procedure to analyse the performance and cost-efficiency of groundwater dams.

Table 16: Cost-efficiency analysis.
Source: (De Trincheria et al., 2017a,b).

Variable	Formula	Description and causes
Annualised construction costs	$AC_{sand\ dam} = CC_{sand\ dam} \times i \times \frac{(1+i)^n}{\{(1+i)^n - 1\}} + AOM_{sand\ dam}$	Where AC are the annualised costs (USD/year), CC are the capital costs of the sand dam (USD), i is the interest rate (%), n is the lifespan of the sand dam (years), and AOM are the annual operation and maintenance costs (USD). • AOM=0 • i= 5% (Jafaar, 2014). • N= 20 years (Batchelor et al., 2011).
Cost-efficiency	$CE = \frac{\text{CC sand dam (EUR)}}{\text{Water Yield (m}^3\text{) or Water Supply (households)}}$ $ACE = \frac{\text{AC sand dam (EUR/year)}}{\text{Water Yield (m}^3\text{) or Water Supply (households)}}$	Where CE is the capital cost-efficiency of the annual water yield (EUR/m³) or supply capacity (EUR/household), and ACE is the annualised cost-efficiency of the annual water yield (EUR/m³·year) or supply capacity (EUR/household·year).

4.8 Specific practical recommendations for subsurface dams

4.8.1 Siting

Subsurface dams require natural deep layers of sand sediments (>2 m) in the riverbed. In addition, the optimum zone for constructing a subsurface dam is generally found on gentle slopes in the transition zone between hills and plains.

4.8.2 Design and construction

The higher technical simplicity of subsurface dams is clear when the siting, design and construction requirements are compared to sand storage dams. Thus, there are not specific design requirements associated to subsurface dams other than the conventional associated to hydraulic retention structures. In addition, Nissen-Petersen (2013) offers a comprehensive analysis of the design and construction of subsurface dams.

For both sand storage dams and subsurface dams, minimising lateral seepage is a priority. Reducing leakage is achieved by compacting clay soil at the base of the dam, or lining it with impermeable material such as plastic lining, in the case of subsurface dams (Nissen-Petersen, 2006a, 2013). Water seepage is minimised if the foundations are not built on fractured rocks or large boulders to prevent seepage. Instead, it is necessary to build on solid bedrocks or key the foundations between 0.6 m and 1 m in solid and impermeable soil.

As it is shown in Figure 32, the construction of a subsurface dam requires to dig a trench until the impermeable foundations of the riverbed and fill it with rubble stones and/or clayey soil, which can be covered by plastic. Alternatively, concrete can also be used. The crest of the weir should be 0.6 m to 1.0 m below the surface of the riverbed, but it is recommended to keep it to 1 m to minimise evaporation losses.

The most clayey soil is determined by filling soil samples into bottomless plastic containers and saturating them with water (Nissen-Petersen, 2013). The soil sample with the slowest infiltration rate is the most clayey soil that can prevent water in the reservoir from seeping through the dam wall.

When a suitable site has been identified, all the sand in the riverbed is removed in a 3-metre wide stretch between the two riverbanks, so that the floor under the sand is fully exposed. There after a 1 m wide trench, called a key, is excavated into the floor right across the riverbed and into the two river banks. The depth of the key must be at least 60 cm into solid soil to prevent seepage under the dam wall.

The best clayey soil identified by testing is transported to the dam site. First, the whole length of the key is filled with a 20 cm thick layer of the clayey soil, which is moistened with water and compacted using either tree trunks or driven forth and back until all air is forced out of the soil. Subsequently, new layers of 20-cm clayey soil are laid out along the whole length of the key and dam wall, and moistened and compacted, until the crest of the dam wall is between 0.6 m to 1 m below the surface of the sand of the riverbed. In addition, the upstream and downstream sides of the dam wall, which should have a slope of 45°, are smoothened using shovels and wooden floats. Also, two short iron bars should be hammered into the riverbanks at each end of the dam wall, to locate the dam wall in the future.

4.8.3 Monitoring and maintenance

If a subsurface dam is properly constructed, it requires no maintenance or monitoring.

4.9 Specific practical recommendations for sand storage dams

4.9.1 Siting

According to Nissen-Petersen (2006) and De Trincheria et al. (2015), there is a need to take into account several additional siting criteria to find a suitable site to implement a cost-efficient sand storage dam. The key siting criteria are:

1. Catchment capable of supplying large volumes coarse and/or medium sand.
2. Suitable riverbeds must have two high river banks to enable the wing walls.
3. Riverbeds with fine textured sand are unsuitable because water extraction rate is low.
4. Wide riverbeds (>25 m) are too expensive for building sand dams.

4.9.2 Design

A high number of sand storage dams become dysfunctional due to poor technical design. The major technical failures are as it follows:

1. Selecting wrong sites in terms of the underground foundations (seepage) and/or the performance / cost-efficiency of the reservoir (i.e. siltation and/or fine sand with low yield).
2. Not adequately considering runoff and sediment transport dynamics, especially the variability of the bedload transport, and therefore, the different volumes of sand sediments transported in the runoff at inter- and intra-annual level.
3. Not considering the water needs of the beneficiaries and the natural yield capacity of the seasonal sandy stream.
4. Building final spillway heights which are too high for the historical water column of the runoff. Thereby, leading to damage of the spillway and/or low infiltration capacity.
5. Building spillways in one stage which inherently have a higher vulnerability and risk of siltation
6. Poor construction procedures that lead to seepage or damage in the spillway.
7. Poor construction procedures that lead to excessive costs and / or use of construction materials.

In addition, most of the design parameters are site-specific and based on the dimensions of the sandy seasonal stream and flood characteristics. Thus, key design criteria for sand storage dams are:

1. To always build the dam wall on an underground dyke to reduce costs and gain free storage.
2. Height of the final spillway should be capable of 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 foundations in murram or clay.

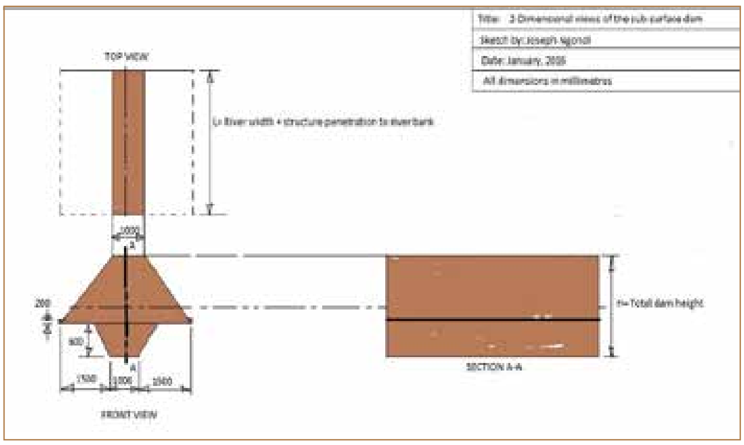


Figure 32: Design parameters of a subsurface dam (left) and construction of a subsurface dam (right).
Source: Adapted from Nissen-Petersen (2013) (left). Photo: E. Nissen-Petersen (right).

4.9.2.1 Reducing costs and free storage capacity

Even though there is a clear relationship between the capacity of a dam and the spillway height, increasing the spillway height causes a direct impact on the construction costs and cost-efficiency, technical complexity and the robustness of the structure. Among others, one fundamental design principle should be to yield as much water as possible without increasing the construction costs. Thus, it is also important to always consider the following recommendations:

1. To always build the dam wall on an underground dyke to reduce costs and gain free storage.
2. Gentler slopes will produce higher throwbacks.
3. Prioritise medium/coarse sand sediments and natural deep layers of sand → higher yield capacity and robustness to evaporation.

4.9.2.2 Height of the final spillway capable of discharging overflow safely

To determine the final spillway height at a specific location, it is required that the water level and the maximum flood level remain below the riverbanks after construction of the dam. This is to prevent the floodwater spilling over the riverbank and creating a new river. Thus, the maximum height of a spillway is dictated by Formula 4:

LR – EFL Formula 4

> Where LR is the height of the lowest riverbank (m) and EFL is the height of the maximum flood level (m).

4.9.2.3 ALDEV design

The ALDEV design (Figure 33) is based on the total final maximum spillway height that allows a safe discharge of overflowing water (Nissen-Petersen, 2006a). Taking this into account, Table 17 highlights the ALDEV recommendations to design cost-efficient sand storage dams.

4.9.2.4 Methodology to build by stages of reduced height

It is recommended to use a range of fixed stage heights from 20 cm to 60 cm on a case-by-case basis. These heights have been obtained from relevant literature focusing on long-term scientific and empirical analysis of sedimentation in sand storage dams in arid and semi-arid areas (Wipplinger, 1958; Nissen-Petersen, 2000, 2006a, 2011; Ochieng et al., 2008). The range of proposed fixed stage heights are given in Table 18 and the methodology to use them on a case-by-case basis is further elaborated in Figures 34 and 35.

The case-by-case variables are as it follows:

1. Final spillway height required to meet local community needs.
2. Type of stream: ephemeral or intermittent.
3. Number of rainfall events during the wet season.
4. Original and target grain-size particle of the reservoir.
5. Assumed historical magnitude of bedload transport.
6. Total construction period time.

De Trincheria et al. (2016b) found that in ephemeral streams, with stage heights from 20 cm to 30 cm in normal rainfall years under unimodal rainfall seasons (8 shower events), it is possible to reach conventional final spillway heights under conventional project cycles of 1-3 years. This is only taking into account that a multi-year historical analysis of the bedload transport is not feasible (i.e. expensive, complex, long-term) in real-life for implementing agencies. In addition, in intermittent streams, with stage heights from 20 cm to 60 cm in normal rainfall years under unimodal rainfall seasons, it is required at least project cycles of 3-5 years.

Building by stages is not more expensive than building in one-stage because most of the construction process is in one go. Thus, average multi-stage spillway construction costs are USD 4,000 in Zimbabwe (De Trincheria et al., 2016b). In fact, a multi-stage spillway construction process that uses the ALDEV design and the key recommendations included in this manual can be significantly less expensive than building in one stage using current construction procedures (Nissen-Petersen and De Trincheria, 2015).

Table 17: ALDEV recommendations for cost-efficient sand storage dams. Source:(Nissen-Petersen, 2006a).

ALDEV variables	(m)
Base of dam	h x 0.75
Slope of front wall	h x 0.125
Base of key	h x 0.55
Vertical back wall	h x 0.2
Width of apron	h x 0.75
Width of crest	h x 0.2
Depth of key	1-2 m

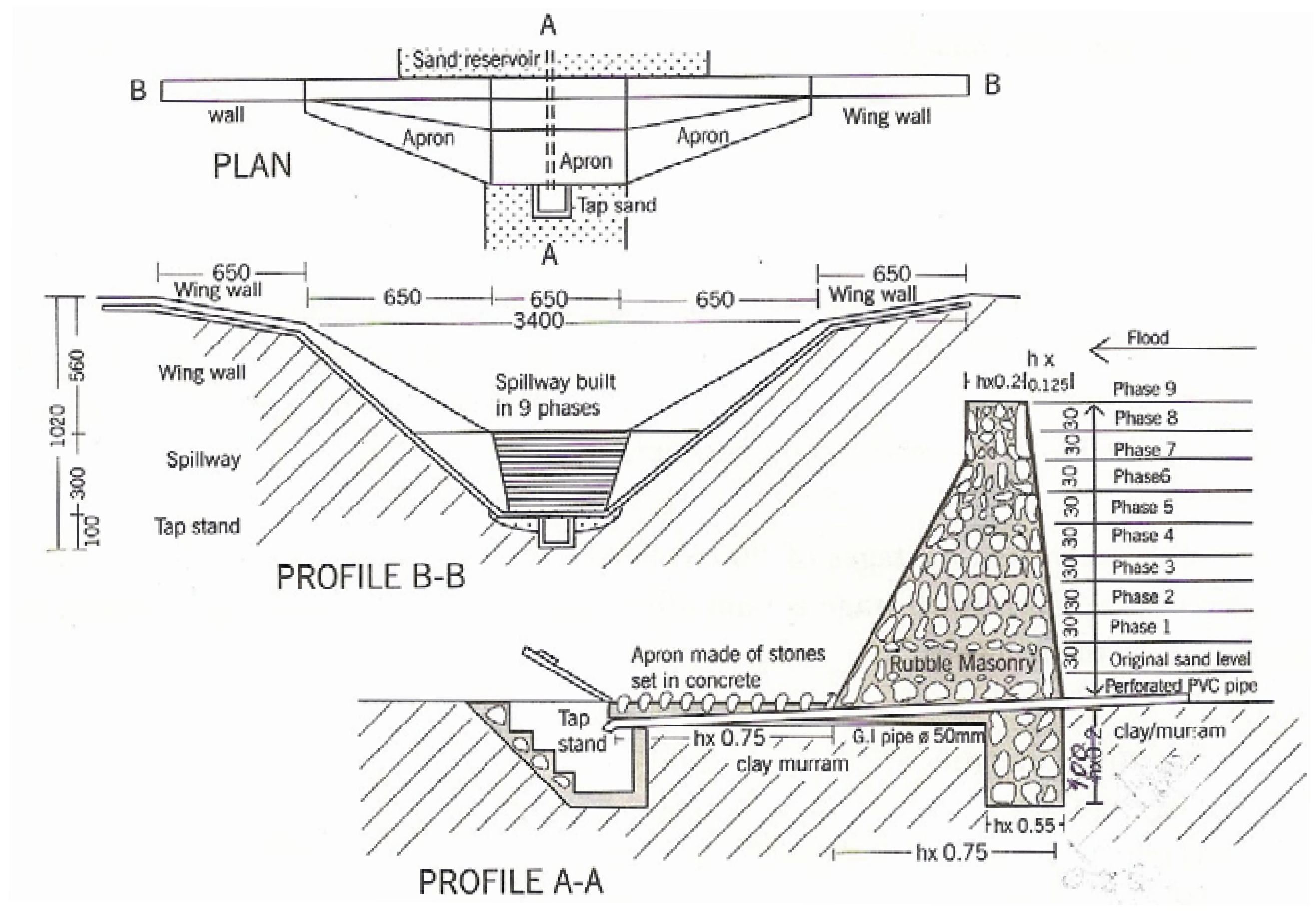


Figure 33: The Aldev design.
Source: (Nissen-Petersen, 2006a).

Stage 1: Spillway is 50 cm above the sand level.

Stage 2: Flood has brought sand to the level of the spillway.

Stage 3: Spillway is raised to 50 cm above new sand level

Stage 4: Flood has deposited sand to the new level of the spillwy

Stage 5: Spillway is raised to 50 cm above new sand level.

Stage 6: This procedure is repeated until the spillway is fully closed.

Figure 34: A multi-stage spillway construction process in an ephemeral sandy stream during the rainy season in Kenya using a stage height of 50 cm.
Source: (Nissen-Petersen, 2006a).

Table 18: Recommended stage heights to be used on a case-by-case basis: CA= Predominant particle grain-size of the original riverbed (C=Coarse, M=Medium, F= Fine); R= Type of seasonal river (I=Intermittent, i.e. continuous flow of water during wet periods; E=Ephemeral, i.e. flow of water only after a rainfall event); S= Number of rainy seasons/year; GR= Predominant particle grain-size of the reservoir created by the sand storage dam; H= Height of stage height in exceptionally good, good and normal rainfall years (m); H(P)= H during poor rainfall years (m).
Source: (De Trincheria et al., 2016b).

#	CA	R	S	GR	H	H(P)
1	C	I	1	C,M	0.3-0.5	0.2
2	C	I	1	F	0.6	0.3
3	M	I	1	M	0.3	0.2
4	M	I	1	F	0.6	0.3
5	F	I	1	F	0.2	0.2
6	C	I	2	C, M	0.3-0.5	0.2
7	C	I	2	F	0.6	0.3
8	M	I	2	M	0.3	0.2
9	M	I	2	F	0.6	0.3
10	F	I	2	F	0.2	0.2
11	C	E	1	C	0.2-0.3	0.2
12	C	E	1	F,M	0.3	0.3
13	M	E	1	M	0.2	0.2
14	M	E	1	F	0.3	0.3
15	F	E	1	F	0.2	0.2
16	C	E	2	C	0.2-0.3	0.2
17	C	E	2	F,M	0.3	0.3
18	M	E	2	M	0.2	0.2
19	M	E	2	F	0.3	0.3
20	F	E	2	F	0.2	0.2

4.9.2.5 Minimisation of seepage losses

Foundation built onto boulders and fractured rocks often drain water out of the dam reservoir, as it is shown in Figure 36. Thus, it is required to build foundations in murram, clay or solid bedrock.

4.9.3 Construction

A sand storage dam is built using rubble stone masonry or reinforced concrete. It is recommended to use always rubble stone masonry which is cheaper than concrete. In addition, reinforcement should only be considered if a final spillway height is constructed. Table 19 shows an overview of key construction issues.

Figure 36: Sand storage dam affected by seepage losses.
Photo: J. De Trincheria.

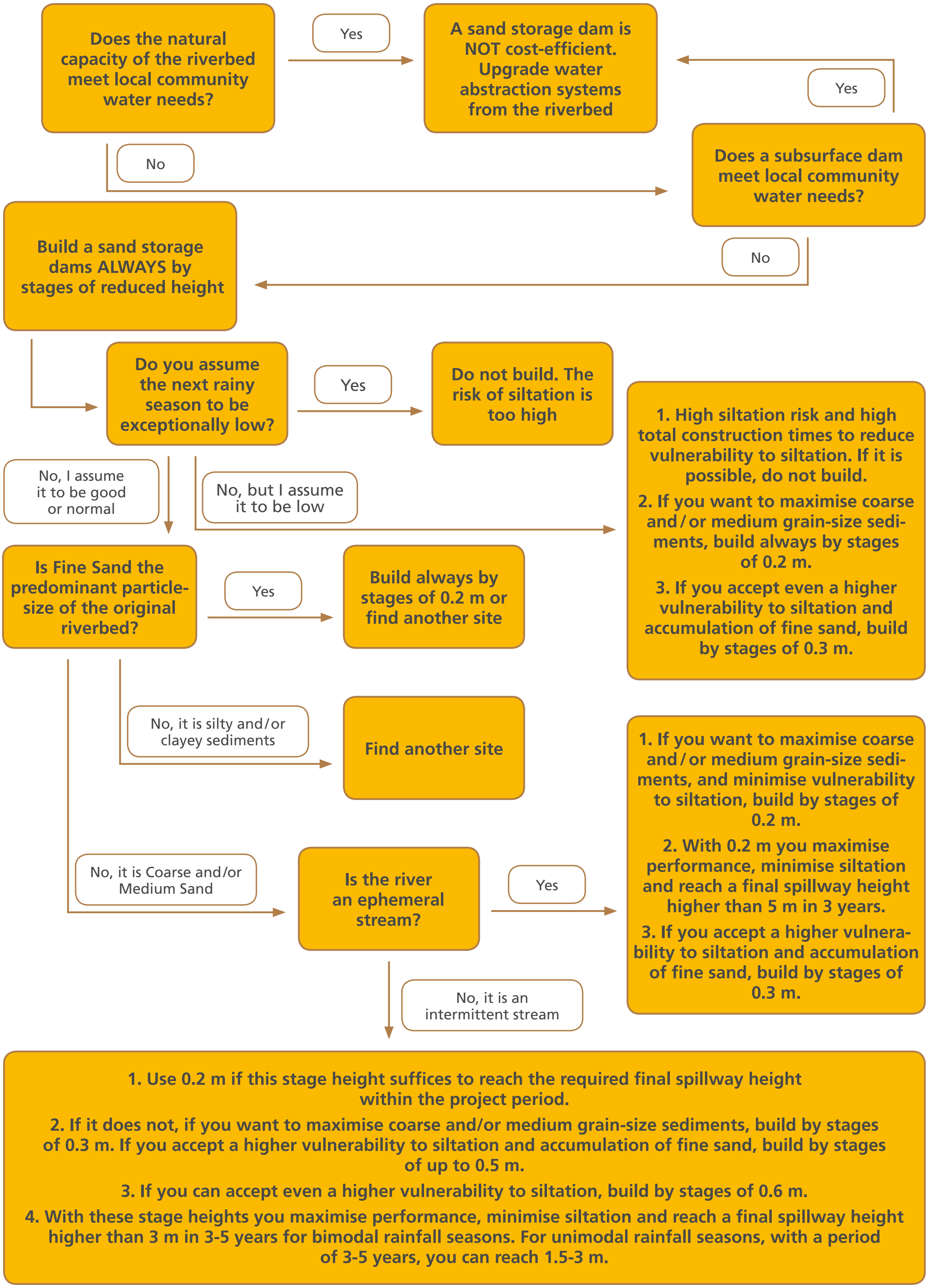


Figure 35: Practical recommendations to use a fixed stage height on a case-by-case basis. Source: (De Trincheria et al., 2016b).

4.9.4 Maintenance requirements

Sand storage dams need careful maintenance and immediate repair of the spillover apron and the wing walls because floods carry large volumes of runoff with abrasive particles, which fall over the spillway and onto the apron below. In addition, flood water can also spill over the wing walls and erode and undermine the river banks. Further, privately owned sand dams can be repaired quickly but maintenance and repairs of community-owned dams takes longer, because the community needs to meet and decide what to do and how to pay for it.

Table 19: Construction and monitoring of different parts of the sand dam.

Item	Materials required	Process brief description	Monitoring
Trench	Mattocks, shovels, wheelbarrows.	Human aided digging or mechanized digging.	Ensure hard pan, or rock is reached.
Reinforcement Columns	Y10, Y8, binding wire, Concrete 1:2:4 ratios of cement: Sand: Ballast. Nails, Timber.	Characteristics of the reinforced columns, if necessary.	Ensure all sizes of reinforced bars are placed and bound.
Foundation Blinding slab	Mortar 1:2:4, Cement: Sand: Ballast.	Mix well with enough water and fill into constructed space.	Ensure correct mixtures, watering and curing.
Foundation	1:4:6, Cement: Sand: Ballast. Y6 bars at 400 mm spacing.	Mix well with enough water and construct appropriately.	Ensure mixture ratios and reinforcement is done. Water for best curing.
Dam	For the upstream wall use plaster 30 mm thick 1: 3 Cement to sand.	Ram strongly, reinforce from end to end, and finish finely and allow complete curing.	Ensure ratios are followed, reinforcement is continuous and watering.
Spillway	1:2:4, Cement: Sand: Ballast; BRC/wire mesh, nil cement for finish.	Ram strongly, reinforce from end to end, and finish finely and allow complete curing.	Ensure ratios are followed, reinforcement is continuous and watering is sufficient, with curing.
Concrete Water Landing	1:4:6, Cement: Sand: Rumble stones /Ballast.	Did the landing position to hard pan and fill downstream on spillway.	Ensure enough sink space is dug and mixtures are correct, and allow curing.

5. ROADWATER HARVESTING FOR OFF-SEASON SMALL-SCALE IRRIGATION

5.1 The technology

Without affecting transport and communication services, roads can be transformed for better use of runoff for off-season small-scale irrigation (Figure 37). In addition, flood control and erosion can be reduced as well. This chapter intends to serve as a guideline on how to combine roads with RWHI management. Thus, once roads are effectively converted in catchment areas that effectively collect runoff during wet periods, different storage systems, especially on-farm ponds (chapter 3) and earth dams (chapter 8) connected with low-cost irrigation systems (chapter 10) can be implemented.

Figure 37: A borrow pit connected to a road acts as a small earth dam. Photo: MetaMeta.

5.2 Advantages and disadvantages

The main points to create water-wise roads and connect them to off-season small-scale irrigation are:

1. Turning runoff on roads into an asset for off-season small-scale irrigation: The water generated from road drainage, i.e. springs opened up by road construction or the water and soil moisture retained by fords and road surfaces, provides a valuable resource that can be stored and subsequently used for off-season small-scale irrigation. In addition, this can also contribute to shallow groundwater recharge, soil moisture and controlling water tables, which can directly or indirectly benefit off-season small-scale irrigation.

2. No damage to landscape, i.e. less erosion and gully formation (Figure 38): Roads disrupt natural drains and creeks and change runoff patterns, often concentrating them across drains. Combining road design and water harvesting structures can tackle these issues and enhance rainfed and irrigated agriculture.

3. Preventing floods: If runoff from roads is not managed, local flooding and uncontrolled sand deposition results, affecting the livelihood of those that live close to the roads. Managing runoff from road can contribute to change and slow down runoff patterns and attenuate floods, which also enhances rainfed and irrigated agriculture.

One concern in harvesting water from roads is water quality, in particular the probability of occurrence of grease and oil from traffic. As part of the UPGro Catalyst Research Programme, water quality from roads was assessed in northern Ethiopia. Using the gravimeter method, water samples were analysed from hand-dug wells and open ponds situated between 10-30 m from the road at four locations. In none of the samples oil/grease was detected. Based on this, there is no cause for immediate concern but vigilance and caution are required, especially

Figure 38: Damage from roads: gullying (left), water logging (middle) and sink holes (right).
Photos: MetaMeta.

in case of surface water bodies. Further, if road water harvesting is done for shallow groundwater recharge, soil media may act as a filter to many biological and organic substances.

5.3 Design and implementation

Depending on landscape typology and land use, road water harvesting techniques vary.

5.3.1 Landscape: mountain, flatland or floodplains

Roads are major interventions in the landscape. Thus, roads dissect surface and subsurface flows and concentrate runoff flows through side-drains, cross-drains and culverts. Therefore, factors like road location in relation to the topography, the steepness of cut slopes, the orientation and the grade of road pavements and the roughness

Table 20: Overview of different landscape factors affecting the use of roads for off-season small-scale irrigation.

	Construction-Maintenance	Drainage characteristics	Vulnerability to erosion	Water harvesting potential
Flatland	Low construction costs if materials are available and soils are stable.	More difficult to drain but depends on soil characteristics. Infiltration structures on waterlogged soils are appropriate.	Waterlogging and scouring of road pavements can be a problem. Side-drains and embankment stability depend on design standards.	Borrow pits, rolling dips, cross-drainage to infiltration areas, hand dug wells, manually drilled shallow boreholes, among others.
Mountain-Valley	Depending on soil characteristics, north oriented roads normally have deeper soils. Thereby, making it easier to construct and carry out maintenance work.	Easier to drain at toeslopes with moderate cross slopes (less than 40%). Ridge tops and valley bottoms are harder to drain.	Depends on roughness of surface, soil characteristics and slope. Portable soils and steep slopes are prone to trigger erosion issues, especially side-drain scouring/gullying.	Spring capture, recharge of borrow pits, water cisterns, side-drains leading runoff to nearby fields.
Floodplain	Elevated subgrades and embankments can increase costs as construction material in floodplains can be scarce.	Laminar flows through floodplains require wide drainage systems, flood control mechanisms such as flap gates or surface drainage outlets.	Waterlogging on buffer areas between road embankments and floodplain. Flood interception: less moisture on downstream areas. This can have major impacts on flood plain agriculture but also on rangeland conditions.	Shallow groundwater: hand-dug wells and manual drilled boreholes as well as dugout ponds and borrow pits.

of slope (rock, soil, vegetation, etc.) are factors to take into account.

As a general rule, road alignments should be set at toe-slopes ranging less than 40% gradient, thus making it easier to drain. If roads are set high on the slope, they may not catch large part of the runoff but if roads are set too low, drainage will be more difficult and road flooding may occur. Roads facing south will dry up quicker than roads facing north. However soils facing north are deeper which facilitates road construction and maintenance work. Table 20 shows an overview of different landscape factors affecting the use of roads for off-season small-scale irrigation.

5.3.2 Categories of roadwater harvesting techniques

Table 21 shows a sets of techniques that can optimise the use of roads for small-scale irrigation.

5.3.2.1 Combining cross drainage / side drains with recharge and storage

The purpose of cross-drains and side-drains (Figure 39) is to evacuate water away from road structures. This is often done without taken into cosideration water recharge, retention and storage principles. Culverts (under-pavement cross-drainage structures) play a mayor role in this regard. The location, size and number of culverts determine drainage patterns and, if done properly, can gear water harvesting from roads. Erosion and siltation issues can be avoided as well. Equally important are side-drains and lead-out ditches (also know as mitre drains).

Collection of water in side-drains and later diversion to recharge structures for off-season small-scale irrigation is an alternative to take into consideration. Road drains may be routed directly to the land (a practice that is common but not universal) on one hand, or to soak pits, small reservoirs and ditches, or other improved structures (Kubbinga, 2012). The advantage of using such recharge and storage systems along the road drain is that they help accommodate and store peak discharges. When the water is applied to the field directly, moisture storage techniques common in spate irrigation are most appropriate: mulching and deep ploughing in semi-arid areas will ensure the availability of water later in the growing season (van Steenbergen et al., 2010).

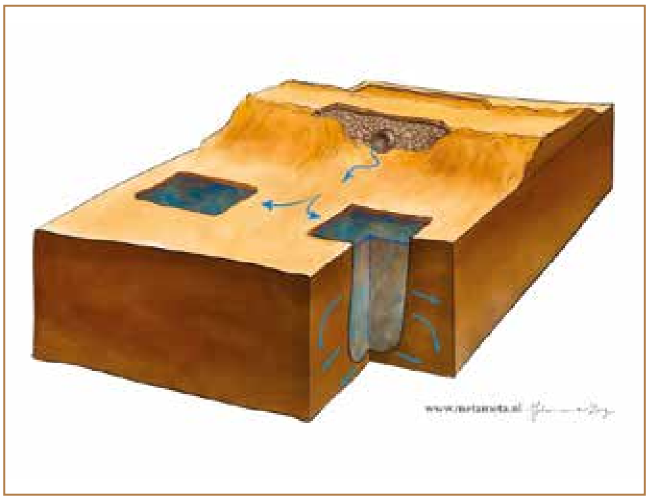


Figure 39: Cross drainage/side drains with recharge and storage. Source: MetaMeta.

5.3.2.2 Borrow pits and dugout ponds

Borrow pits (Figure 40) can be systematically used as recharge, storage or seepage ponds. Borrow pits are excavations done to collect materials, i.e. sand, gravel, soil, for road construction and are usually located very near to the road itself. After the road is finished, if not refilled, borrow pits are left unused. However, these pits may be filled with water after rains. The shape and size of the ponds are relevant: Whereas round shapes maximize effective storage, deeper ponds have less evaporation losses.

Depending on the soil conditions and geology, borrow pits can also be used as recharge ponds for off-season small-scale irrigation at no additional cost (Nissen-Petersen, 2006c). In areas with permanent shallow groundwater, borrow pits also serve as dug-out ponds filled with water seeping in from adjacent shallow aquifers. Such ponds have become an important source of water for irrigation or livestock in dry flood plain areas in Ghana or South Sudan.

Table 21: Road harvesting techniques.

1	Combining cross drainage/side drains with recharge and storage.
2	Borrow pits and dugout ponds - beneficial use of excavation material.
3	Clever road foundations.
4	Spring capture.
5	Water spreading weirs/ sand dams combined with river crossings.

Figure 40: A borrow pit made from the excavated soil of a road construction.
Photo: MetaMeta.

5.3.2.3 Clever road foundations

Road foundations may interfere with subsurface flows that feed shallow wells. The road foundations depend on the road and traffic type. Tarmac roads may have impervious bases 2-5 m thick, but such compacted road foundations are not common for dirt roads. Impermeable subgrades and road foundations can block subsurface flows altering the availability of shallow groundwater and drying up shallow wells on the lower end of the road and increasing water tables on the upper end of the road.

Groundwater drainage systems and cross-drains can help revert this situation. Permeable subgrades or lateral drains (water table lowering, e.g. trench drains and California drains), transverse drains in rigid pavements, earthworks drains (e.g. drainage spurs and cut-off drains), and pavement under-drains can be used to control flows entering the road subgrade and foundation (Santinho Faisca et al., 2008). These structures have the primary objective to protect the road from water intrusion in the road structure. However, careful placement of these structures allows control of water tables and by-pass road blocking from upstream to the downstream.

5.3.2.4 Spring capture

When roads cross hilly areas and the roads are laid in deep cut-slopes of terrain, excavation may open springs in mountain aquifers. These newly opened springs can damage cut slopes and erode land. Drainage masks protect cut slopes from spring flows infiltrating water to the road drainage system. Likewise, protection boxes for newly opened springs collect the spring water and can either be diverted to infiltration structures (such as soakaways) or used directly in surface storage structures, either open ponds or cisterns. It is important to estimate the discharge of these spring flows so as to properly dimension the collection tanks and create spill-over structures. The newly opened springs can be used as water supply sources, especially in semi-arid regions.

5.3.2.5 Water spreading weirs / sand dams combined with river crossings

When dirt roads cross seasonal streams, it is common to construct fords (also known as low causeways, drifts or Irish bridges). These road crossings can help retain groundwater upstream of the road crossing and can increase bank infiltration.

These structures can have multiple functions. The first is to allow road traffic to cross the stream. The fords can however also double up as a proxy sand storage dam, trapping coarse sediment behind them and creating an artificial shallow groundwater reservoir that can store and retain water, as it is shown in Figure 41. However, the spillway of the sand storage dam should be built by stages of reduced height between 20 cm to 60 cm. In addition, the foundations should reach the impermeable layer so as to minimise seepage losses. Fords combined with roads also have another function, which is to stabilize the seasonal stream as a result of the deposition of the sediments transported by the stream upstream of the ford.

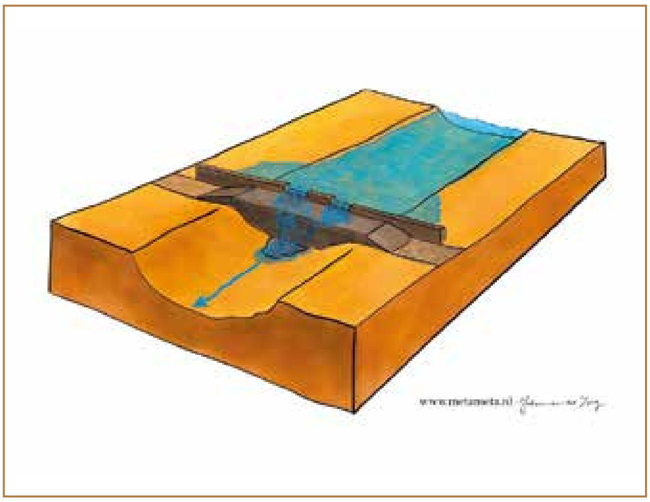


Figure 41: A diagram of a sand storage dam.
Source: MetaMeta.

6. ROOF CATCHMENTS FOR OFF-SEASON SMALL-SCALE IRRIGATION

6.1 The technology

Rainwater harvesting with roof catchments is a technique where runoff generated on rooftops is captured, conveyed and stored in reservoirs (i.e. on-farm ponds) and/or tanks. With a good design, roof catchments can provide water for off-season small-scale irrigation at household level, namely kitchen gardening. The size of the roof catchment coupled with the financial capability of the beneficiary determines the volume of rainwater that can be harvested in a given area and thus, the reservoir/tank size. The water harvested from the roof is the product of the roof catchment area and the total rainfall amount.

Roof catchment systems have a lot of storage options given the fact that the catchment is raised well above the ground in comparison to ground catchments. They are thus categorized into the following reservoir types highlighted below. Figures 42, 43 and 44 show a roof catchment RWH system connected to an on-farm pond, a spherical underground tank, and a surface tank, respectively.

1. Roof catchment with surface reservoirs and/or tanks, among them, on-farm farm ponds and plastic tanks.

2. Roof catchment with underground tanks, i.e. spherical or sausage tanks.

Although water supply from the roof has usually been limited to kitchen gardening due to the high costs and limited storage capacity of tanks, using on-farm ponds as the storage structure has the potential to expand their scope and applicability to small-scale horticultural production using drip irrigation and/or greenhouses. Thus, farm ponds are cheaper than tanks, and hence make roof catchment systems more cost-effective.

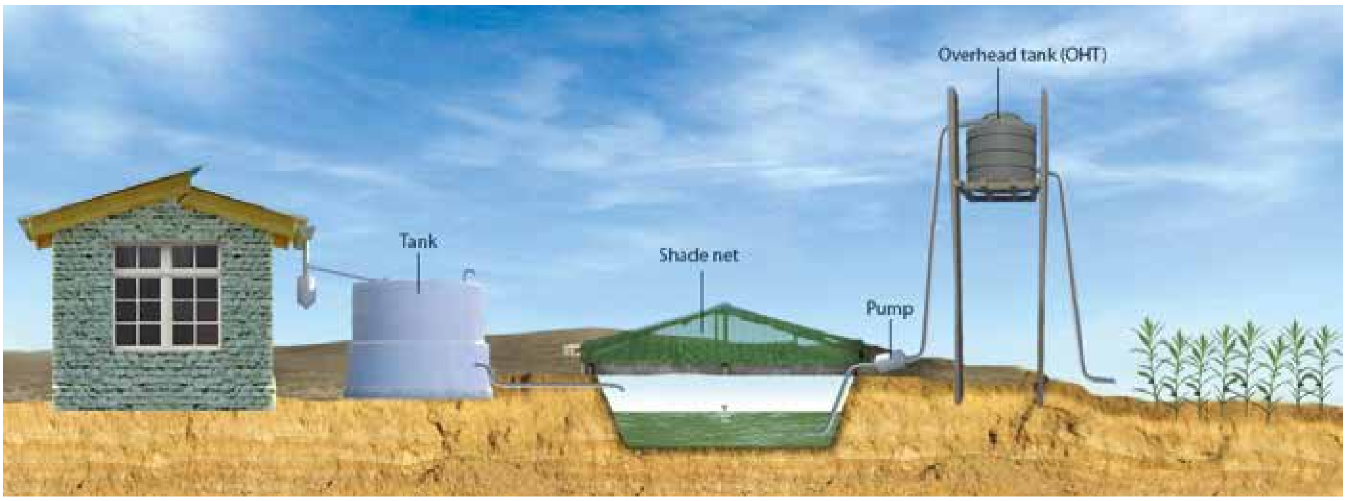


Figure 42: A roof catchment system coupled with an on-farm pond and a water tank (optional).
Source: Pixiniti Studios.

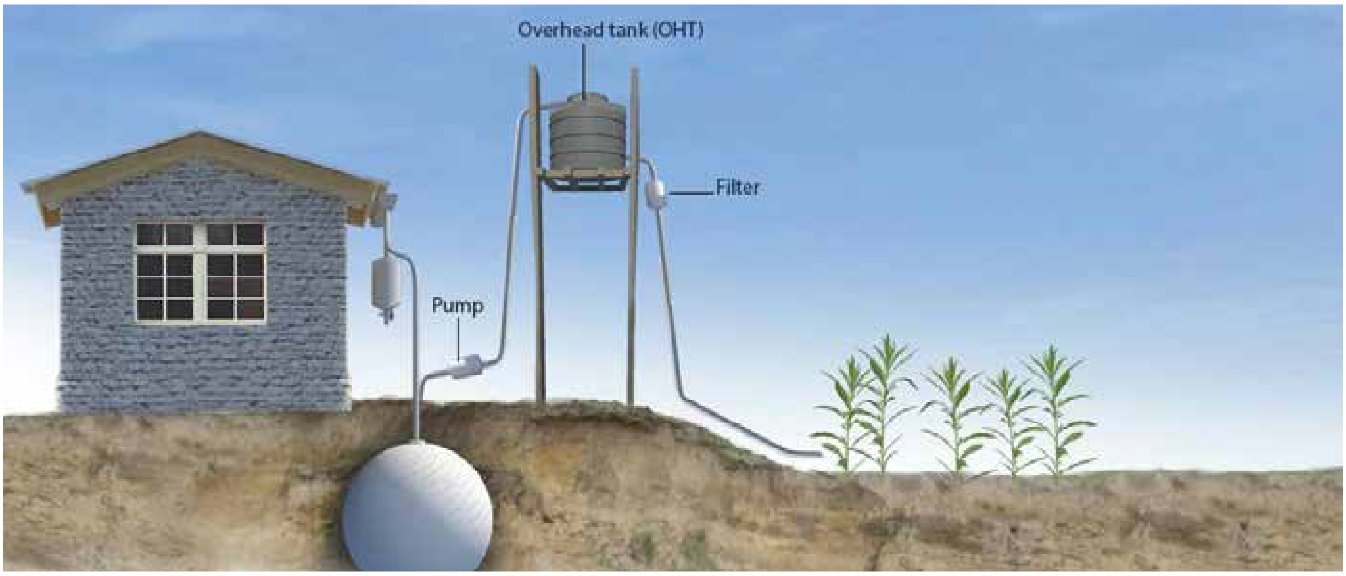


Figure 43: A roof catchment system coupled with an underground spherical tank. Source: Pixiniti Studios.

Figure 44: A roof catchment system coupled with a surface water tank. Source: Pixiniti Studios.

For example, the cost of a 50 m^3 farm pond roofed with simple metallic structure and shade net is USD 1,000 compared to the conventional costs of USD 1,500-2,000 for a ferro-cement tank and USD 10,000 for a plastic tank of same storage capacity. However, several key innovations have taken place in Honduras in the form of an elevated impluvium tanks of 23 m^3 which is connected to a small roof with a gutter system that drives water by gravity to a low pressure drip irrigation system for EUR 1,000 (IDE, 2017) (Figure 45, left). Also in Honduras, 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 have recently been implemented (Kadet, 2017) (Figure 45, right).

Figure 45: An impluvium tank (left) and a geomembrane bag (right) in Honduras. Sources: (IDE, 2017 -left- and Kadet, 2017 -right-).

Table 22: Advantages and disadvantages of roof catchment systems.
Source: (Hatum and Worm, 2006; Nissen-Petersen, 2007; Gur and Spuhler, 2010; Shrestha, 2010; CARE, 2017; IDE, 2017).

Advantages	Disadvantages
• **Household-based systems:** Little distance between the water storage and the application area. Also, users can usually maintain and control themselves the system.	• **Yield:** The amount of water generated from the roofs is limited by the amount of rainfall and the size of the catchment area and storage reservoir. This affects the potential area to be irrigated. Usual storage volumes connected to household roof catchment systems are 50 m^3.
• **Technical simplicity:** Local communities can effectively be trained to replicate the system with little external support. This reduces costs and strengthens ownership.	• **Supply is sensitive to droughts:** Occurrence of long dry spells and droughts can cause water supply problems.
• **Flexibility:** Not affected by local geology or topography. Almost all roofing material is acceptable for collecting water for household purposes.	• **Costs:** The costs are strongly correlated to the volume of water to be stored. Therefore, high capital investment costs which are not usually affordable for smallholders are required for small-scale irrigation purposes. For 50 m^3, the costs for plastic tanks, which are easily available in local markets, are not lower than USD 10,000. However, for the same capacity, a ferro-cement tank costs 1,500-2,000 USD. In addition, costs can be around 1,000 USD if on-farm ponds, impluvium tanks or geomembrane bags are used.
• **Water quality:** The water quality is usually better than surface and/or groundwater sources. Also the water can effectively be used for domestic purposes.	• **Cross-contamination:** The water quality of the stored water may be affected by organic cross-contamination.
• **Reliability:** No siltation- and/or evaporation-related problems.	
• **Maintenance:** Little time and energy required to maintain and/or operate the system.	

6.2 Advantages and disadvantages

Table 22 highlights key strengths and weaknesses of roof catchment systems for off-season small-scale irrigation.

6.3 Siting

The siting of a roof catchment system is influenced by the nature and size of roof catchment, the slope, and the purpose for which the water is needed. The following considerations should be taken into account:

1. If the tank is on the surface and the rainwater collected is also intended for domestic use, the tank should be located behind or besides the house to improve its access and aesthetics. In addition, the tank must be located below the roof gutters to enable direct flow into the tank.

2. If the tank is underground, it can be located anywhere but not close to a source of contamination such as a septic tank.

3. When harvesting water from large roofs of institutions, i.e. schools, churches or government buildings, then the roof sections and gutters can be split to allow for multiple placements of tanks.

6.4 Design

The design of a roof catchment rainwater harvesting system revolves around calculating the optimum size of the storage reservoir to meet the beneficiary's needs. The storage size is influenced by rainfall distribution, the dimensions and physical characteristics of the roof catchment, and the water requirements. These factors are to be coupled with the financial capability of the beneficiary. Further, the following key factors should be taken into account:

1. The design of roof water harvesting system should encompass an overflow pipe to enable discharge of excess water, which may be used for shallow groundwater recharge.

2. An automated foul flush mechanism should be installed along the downpipe to ensure that impurities in the water are safely by-passed away from the tank.

6.4.1 A quick method to calculate the optimum size of the storage reservoir

SamSam Water has developed a web-based and Android application called “Rainwater Harvesting Tool” that estimates the optimum size of a roof catchment system. The tool automatically provides data on monthly rainfall averages according to a specific location. With this data, the roof catchment area and the surface type (i.e. iron/metal sheets, tiles, flat roof or thatched) and the water requirements, the size of the roof catchment system is estimated. The tool is accessible at **http://www.samsamwater.com/rain/** and the application can be downloaded at **https://play.google.com/store/apps/details?id=com.b24.samsamwater**.

A more detailed calculation of the optimum size of the reservoir can be carried out by determining the monthly average rainfall, the roof catchment characteristics and the rainwater harvesting potential of the roof catchment.

6.4.2 Determination of the monthly average rainfall

Monthly rainwater averages can be obtained from several sources, among them, the nearest local meteorological station or a meteorological department.

6.4.3 Roof catchment characteristics

Roof catchment characteristics include the catchment area, pitch factor and surface conditions. The roof catchment area (m²) can be easily estimated by multiplying the length and width of the roof. Further, the roof pitch factor refers to the roof slope and different values can be obtained in relevant literature. Roofs with a higher roof pitch can harvest more rainwater than roofs with a lower roof pitch.

In addition, the roof coefficient refers to the coefficient of the roof surface. Different values for the runoff coefficient are shown in Table 23. The coefficient is used as one of the factors for calculating the amount of runoff harvestable from a roof.

Table 23: Runoff coefficient for various roof covers. Source: Adapted from Hatum and Worm (2006).

Roof material	Runoff coefficient
Metallic/Iron roof	0.95
Asphalt and concrete	0.9
Tar and gravel	0.80-0.85

6.4.4 Roof catchment potential using the Double Mass Curve Analysis (DOMCA)

Computation of the roof catchment rainwater harvesting potential at household level involves determining the monthly cumulative roof water supply and the monthly cumulative water on one hand, and calculating the monthly difference between these two parameters at annual level on the other, as it is shown in Table 24 and Figure 46. The monthly roof water supply is given by Formula 5:

$R_fWH_s = A_f \times P \times C_f \times P_f \times n$ Formula 5

> Where R_fWH_s is the monthly volume of harvested water from the household roof (m³), A_f is the area of the roof surface (m²), P is the monthly precipitation (m), C_f is the roof runoff coefficient, P_f is the roof pitch and n the probability of rainfall occurrence.

In addition, the monthly household water demand is given by Formula 6:

$R_fWH_{MD} = HH_{size} \times HH_{MWC}$ Formula 6

> Where R_fWH_{MD} is the monthly household water demand (m³), HH_{size} is the household size (m²) and HH_{MWC} is the average monthly water consumption /demand (m).

Therefore, the reservoir size is dictated by the month which produces the highest volume given by Formula 7:

$R_V = R_fWH_s - R_fWH_{MD}$ Formula 7

Table 24: An example of a DOMCA table for computing roof water reservoir size.

Parameter	April	May	June	July	August	September	October	November	December	January	February	March
Rainfall (mm)	320	208	68	4	0	0	200	115	25	9	0	14
Total road area (m²)	100	100	100	100	100	100	100	100	100	100	100	100
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	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Roof Pitch	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Monthly roof water supply	21.39	13.90	4.54	0.27	0.00	0.00	13.37	7.69	1.67	0.60	0.00	0.94
Cummulative roof water supply (m³)	21.4	35.5	39.8	40.1	40.1	40.1	53.5	61.2	62.8	63.4	63.4	64.4
Average household size	6	6	6	6	6	6	6	6	6	6	6	6
Average per capita water consumption (m³)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Cummulative household water demand (m³)	1.5	3.0	4.5	6.0	7.5	9.0	10.5	12.0	13.5	15.0	16.5	18.0
Reservoir site (m³)	20	32	35	34	33	31	43	49	49	48	47	46

From Table 24, the reservoir size is 49 m³ because this is the highest number annually together with December. Figure 46 shows a DOMCA graph depicting the month with the largest volume which denotes the reservoir size.

For further guidelines on design of roof catchment rainwater harvesting systems, the following manuals are recommended to be used: Hatum and Worm (2006), Nissen-Petersen (2007), Thomas and Martison (2007) and Studer and Liniger (2013). In addition, the Sustainable Sanitation and Water Management Tool also offers comprehensive information on roof catchment rainwater harvesting systems at **http://www.sswm.info/category/implementation-tools/water-sources/hardware/precipitation-harvesting/rainwater-harvesting-r**.

6.5 Operational requirements

In order to avoid cross-contamination of the storage tank during the first rains, roof catchment systems should incorporate first flush-like systems that ensure that organic material accumulated during dry periods enters the tank (Gur and Spuhler, 2010). Below two systems that are recommended to be used.

6.5.1 Roof water harvesting system with a floating ball foul flush mechanism

Figure 47 shows a floating ball foul flush mechanism. The foul flush mechanism consists of a chamber designed to capture up to 2% volume of the heaviest storm event, which is referred to as the foul flush. When runoff flows

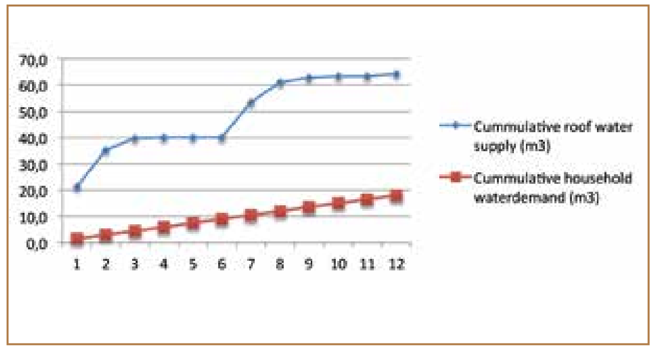


Figure 46: A DOMCA graph depicting the month with the largest volume which denotes the reservoir size.

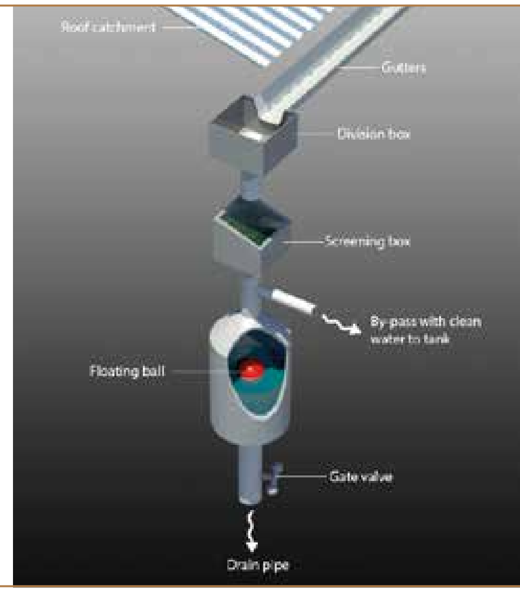


Figure 47: A floating ball foul flush mechanism. Source: Pixiniti Studios.

from the roof goes first to the foul flush chamber until it is full. Then, all the foul flush has been trapped as the ball rises and closes entry into the chamber. The remaining runoff will then be re-routed towards the tank via the sand filtration system.

6.5.2 Roof water harvesting system with a separator pipe foul flush mechanism

An automated foul flush mechanism uses a separator pipe and a sand filter. As in the previous case, the separator pipe is designed to capture up to 2 % volume of the heaviest storm event, which is referred to as the foul flush. When runoff flows from the roof goes first to the separator pipe. After the separator pipe has been filled with the foul flush, the remaining runoff will be re-routed towards the tank via the sand filtration system.

6.6 Maintenance Aspects

Before the onset of the rains, there is a need to remove any organic material that may have been deposited in the gutters and/or washed onto the mesh-box. It is also required to ensure that no foul water is still stored in the foul flush chamber or separator pipe. Table 25 shows the main issues with regard to the monitoring and maintenance of roof catchment RWH systems.

Table 25: Monitoring and maintenance of roof water harvesting system.
Source: (Hatum and Worm, 2006).

System components	Monitoring and maintenance aspects
Gutters	Before the onset of rains, check the gutters by pouring water at the end opposite of the downpipe. The water will flow through it. Get a plumber to repair any spot where leakage is noticed.
Screen box	Remove any material still stuck on top of the screen.
Gate valve below foul flush chamber	Check and ensure that the valve is closed so that the roof runoff is not all lost through the foul flush mechanism.

7. ROCK CATCHMENTS FOR OFF-SEASON SMALL-SCALE IRRIGATION

7.1 The technology

A rock catchment (Figure 48) uses natural rock surfaces to divert rainwater to a central storage area, i.e. rock dam, small earth dam or a surface or underground tank (Nissen-Petersen, 2006b). Rock catchments can collect up to 90 % of the total rainfall in the catchment area, which provides a valuable water supply even when rains are below normal levels. For off-season small-scale irrigation, rainwater should be stored as a surface reservoir with capacities from 50 m³ to 4,000 m³ (Akvo, 2015a).

To facilitate the collection of runoff into the storage reservoir or tank, rainwater is gravitated into the reservoir following the conveying lines of garlands made of rocks mortared onto the rock surface (Nissen-Petersen, 2006b). In addition, the gutters should follow the contour but have a minimum slope of 3% and be high enough to direct water (Nissen-Petersen, 2006b). Further, a stonewall is usually built with stones and mortar around the outer edge of the rock catchment.

7.2 Applicability and scalability

Most drylands in sub-Saharan Africa have suitable sites with large rock outcrops where a lot of runoff is generated after rains. Some rock surfaces are exposed/bare while others are invisible because are covered by soil and vegetation (Nissen-Petersen, 2006b). By means of the development of a rock surface into a catchment area, the runoff can be harvested and stored for off-season small-scale irrigation by means of surface reservoirs. The capacity of rocks to supply water is significant because a rock surface of 1 ha can provide 1,000 m³ from 100 mm of rainfall (Akvo, 2015a). Thus, even low and erratic showers can supply large volumes of water if the catchment area is large enough. (Akvo, 2015a).

Rock catchments are the most economical and reliable water source in semi-arid, arid and desert regions where saline groundwater and/or no seasonal streams are available (Nissen-Petersen, 2006b). The construction process is labour-intensive but community participation make it a cost-effective and viable option in most rural areas. Further, rock catchment systems have no negative environmental impacts. A positive impact is that rock catchments harvest rainwater that otherwise would cremte soil erosion and flooding problems for people living adjacent to the rocks (Nissen-Petersen, 2006b).

If connected to a surface reservoir, their potential for off-season small-scale irrigation is high (Nissen-Petersen, 2006b). If connected to a tank, their only limitation is their ability and reliability to supply enough water for small-scale irrigation. However, in these cases, they can support kitchen gardening. Rock catchment present also challenges, which limit their applicability and scalability. Table 26 shows an overview of key strengths and weaknesses.

7.3 Siting

When selecting a suitable site, it is important to consider the 4 components of a rock catchment system (Nissen-Petersen, 2006b):

1. A catchment area of clean rock surface from where rainwater can be collected without obstruction. Rocks can be cleaned by removing soil, vegetation, stones and loose parts from the surface. Large fissures can be sealed with cement mortar or concrete. Smaller cracks can be sealed with bitumen.

Table 26: Advantages and disadvantages of rock catchment systems.
Source: Nissen-Petersen, 2006b; Akvo, 2015a.

Advantages	Disadvantages
Most cost-efficient alternative in sites with saline groundwater, low rainfall, and no rivers.	Only applicable where there are rock outcrops.
The rock catchment is highly efficient collecting rainwater with low infiltration rates.	The quality of water might be low if a catchment and reservoir are not cleaned before rainy season.
The water supply potential is large because the rock catchment area is usually large.	Mosquitoes breed in open reservoirs and spread malaria.
Easily linkage with gravity-based pumping and irrigation systems because of the elevated position of the rock catchment.	High evaporation losses if the reservoir is open.
The rock catchment does not occupy farmland.	Leakage and seepage losses due to poor workmanship and low construction skills.
Rock catchments do not imply ownership issues as they are common resource.	Limited water supply for small-scale irrigation when coupled with tanks. Instead, water for irrigation can be provided from earth dams situated at the foot or near the rock catchment.
Relatively low and low-cost maintenance requirements as it only requires to clean the catchment area.	Costs are potentially high especially for building tanks that store water directly. For a rock catchment with 2 water tanks of 90 m^3, costs are USD 8,240 (USD 46/m^3). For a rock dam with 300 m^3, costs are USD 4,000 (USD 13/m^3). For an earth dam with 400 m^3, costs are USD 2,000 (USD 5/m^3).
High acceptability.	Construction is labour-intensive.
Low vulnerability to siltation and seepage.	
High water quality if the catchment area is kept clean.	
The conveyance systems are made of locally available materials.	

2. Garlands of gutters divert runoff from a catchment to a water reservoir. Gutters can also be used to increase the catchment area of rocks. Aqueducts can deliver water from gutters to water tanks and transport water from adjacent rock surfaces to the main catchment area.

3. A water reservoir that can be a water tank, a rock catchment dam or an earth dam.

4. Application of water from the rock catchment to the crop area.

7.4 Design and construction

According to Nissen-Petersen (2006b), runoff from a rock surface is gravitated to a reservoir by long lines of garlands made of rocks mortared onto the rock surface. The water reservoir must always be located at a lower level than the catchment area in order to facilitate the flow of water by gravity. The water reservoir can be a tank located near the rock catchment, a surface dam built of rubble stone masonry or a small earth dam (Figure 49).

7.4.1 The rock catchment

The rock catchment is the area of continuous rock outcrop where runoff is generated from incoming rainfall. The amount of runoff harvested from a rock catchment is determined by the effective catchment area enclosed

Figure 48: A rock catchment and system of tanks.
Photo:: E. Nissen-Petersen.

Figure 49: A rock catchment with a tank (left) and a dam on the rock itself (right). Photos: J. de Trincheria and E. Nissen-Petersen.

by the gutters, the shape of the catchment in relation to storage structure location, the amount of seasonal rainfall, the water losses through the rock surface, and the size of the storage structure based on water requirement (IRHA, 2011).

7.4.2 The conveyance mechanism

Design and installation of the conveyance mechanism for the runoff generated over a rock catchment is simple. It entails cleaning the rock surface and constructing stone gutters on the lowest areas of the rock catchment. Gutters made of stones built at a gradient of 0.5% are sufficient to convey runoff flowing from the upper sections of the catchment.

7.4.3 The water reservoir

The reservoir can either be constructed within the lowest section of the rock catchment, or outside 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, as it is shown in Figure 50. If the reservoir is constructed outside the rock catchment, then it can be a tank, i.e. concrete ferro-cement tank, a rubble stone ferro-cement tank or a PVC tank, or a small earth dam.

The water storage tank or masonry gravity dam should be designed considering the water requirements and effective catchment water yield. The masonry gravity dam

Table 27: Calculation of the runoff production and reservoir size of a rock catchment.
Source: (Nissen-Petersen, 2006b; Akvo, 2015a).

Runoff production
1. Determine water requirements (R, L/day).
2. Estimate area of reservoir (A, m²), evaporation losses from reservoir (E, mm / day) and volume losses per day (A x E, L / day).
3. Estimate length of critical period during which water entering the catchment is less than water requirements and losses (T, days).
4. Estimate average rainfall entering the catchment reservoir during critical period (Q, L/day): Rainfall x Catchment area x Runoff coefficient (usually taken as 0.9).
5. Adjust catchment area which decreases with increasing slope (e.g. 23 % fewer m² if slope is 40 %).
6. Calculate effective storage required (S, L) = (R + (A x E) – Q) x T

Table 28: Calculation of the runoff production and reservoir size of a rock catchment.
Source: (Nissen-Petersen, 2006b; Akvo, 2015a).

Reservoir size
7. Determine area of reservoir (A, m²) through topographical survey for different values of water level (D). This is to find a reservoir capacity greater than storage required (S) to allow for a safety margin. Reservoir capacity is estimated from: (Length x Width x maximum Depth) / 6.175.
8. Determine height of the dam, which should be D + 1 m (precautionary principle).
9. The base of the dam wall should be 3/5 of its height in order to eliminate the use of reinforced walls.

Figure 50: Mulinde rock catchment in Kitui, Kenya.
Photos: L. Ojwang.

should be on the outer edge on a depression of the rock surface. According to Nissen-Petersen (2006b) and Akvo (2015a), the reservoir size can be decided according to water demand, evaporation losses, length of critical period and average rainfall. Tables 27 and 28 show the variables to take into account.

7.4.4 Application of water from the rock catchment

Given the high runoff generation capacity of rock catchments, the runoff harvested can be used for off-season small-scale irrigation and other purposes like domestic or livestock uses. However, to use a rock catchment system for small-scale irrigation, the water reservoir should preferably be a rock dam on the rock itself or an earth dam.

7.5 Monitoring and Maintenance

Table 29 shows an overview of the main monitoring and maintenance actions of a rock catchment system.

Table 29: Summary of monitoring and maintenance actions for rock catchments.
Source: (Nissen-Petersen, 2006b; IRHA, 2011; Akvo, 2015a).

Variable	Monitoring during construction	Basic monitoring and maintenance actions
Catchment area	Let the rock catchment area be flattened using a hammer as much as possible to make it easy to maintain.	Before every downpour collect and remove all detritus from the catchment area. Remove any detritus deposits on the rock.
Garland of gutters	Make garlands with smooth finish and of sufficient height so that all water is collected.	Observe if any water is overflowing the garlands, and increase their height. Clean all the catchment and garlands. Fence the rock catchment area to minimize accidents and reduce pollution.
Water reservoir	Inspect all water reservoirs for water loss and cracks.	Repair any damaged water reservoirs. Repair all gates and lids for water reservoirs. Clean the water reservoirs every year, or every time it is empty, just before rains.
Water draw points, i.e. wells, pipes	Ensure all water draw points constructed during dam construction are properly secured to avoid damage by any external agents.	Clean all water draw points. Replace damaged parts. Check the water levels using pressure or visual indicators to inform on the applications for the water.
Water quality	n/a.	Confirm the water quality after every rain season to advice on the various uses. Put a tag on the quality of water on the pipe or community water draw point.

8. SMALL EARTH DAMS FOR OFF-SEASON SMALL-SCALE IRRIGATION

8.1 The technology

A dam is a hydraulic retention structure built on a water course to retain water upstream of thestructure and control the flow of water (MWI, 2015). Generally dams can be classified into three types, i.e. earth dams, rubble stone masonry dams and concrete dams. This chapter focuses on small earth dams for off-season small-scale irrigation.

An earth dam (Figure 51) has an embankment made up of soil. It is cheap and relatively easy to construct. Earth dams are used to impound and store runoff for multiple uses (Stephens, 2010). Earth dams are often built on valley sections with embankments anchored on the downhill side, while water is impounded on the upstream side. The embankment height of earth dams typically does not go beyond 5 m and relies on its mass to resist sliding and overturning due to the hydraulic forces acting upon it (Stephens, 2010; Nissen-Petersen, 2015).

According to Stephens (2010) and Nissen-Petersen (2015), a small earth dam on a hillside or valley section is very cost-effective in creating a water storage reservoir. In comparison to other water conservation structures, earth dams provide a high water storage capacity per m^3. Small earth dams with storage capacities below 5,000 m^3 may be built using human labour, animal power or farm machinery power. Medium-sized and large earth dams, with storage capacities usually higher than 10,000 m^3 are built with machinery power.

Earth dams can be classified into two categories: homogeneous (i.e. made of one type of soil) and zoned (i.e. made of two or more types of soil) (Stephens, 2010), as it

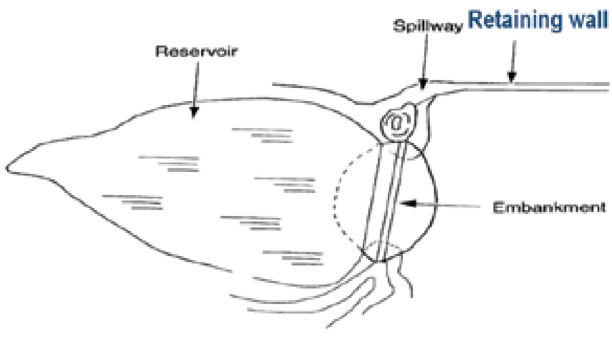
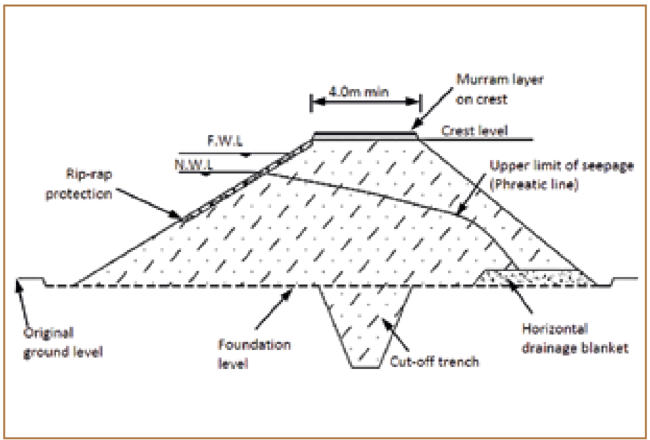


Figure 51: Basic components of a dam.
Source: (MWI, 2015).

is shown in Figure 52. In case the foundation is pervious, a cut-off made from impervious material is used to control seepage. A zoned dam is made of pervious or semi-pervious material with an impervious clay or silt clay core in the middle.

Small earth dams often use a homogeneous embankment that does not require zoning in the middle. Zoning is only done for large dams to reduce seepage. The seepage line at full supply capacity (FSC) is also known as phreatic line. In order to reduce risks emanating from build-up of excess pore space, it is important to have relatively flat slopes of 1:3 on the upstream side and 1:2 on the downstream side. Either a rock toe on the downstream side or clay blanket on the upstream slope is important to reduce the risk of structure failure. The embankment is best placed on an impervious foundation as it allows the inclusion of a cut-off drain that discharges seepage water during full supply level.

In order to make use of the water stored in the reservoir, a small earth dam is usually provided with an outlet. The outlet may be a pipe buried in the dam embankment or



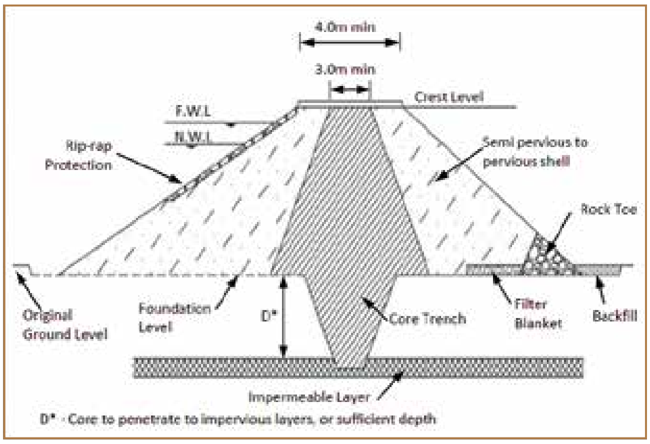


Figure 52: A homogeneous dam with a cut-off (left) and a typical zoned dam (right).
Source: (MWI, 2015).

dam foundation, or it can be a simple siphon pipe. While it requires more skill to install the buried pipe, a siphon system is easily installed and is recommended for existing small earth dams. The buried pipe is normally installed during dam construction, and the inlet is a filtration cage made of welded mesh and graded aggregates. Figures 53 and 54 shows a small earth dam with and without a drainage system.

8.2 Advantages and disadvantages of small earth dams

The advantages and disadvantages of small earth dams are highlighted in Table 30.

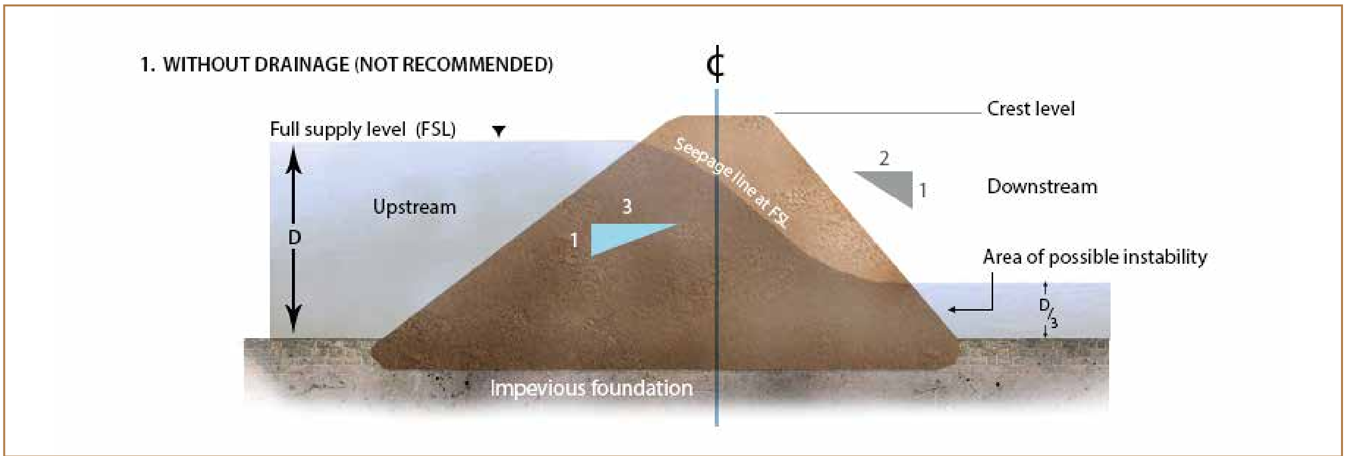


Figure 53: Small earth dam without drainage (Not recommended).
Source: Pixiniti Studios.

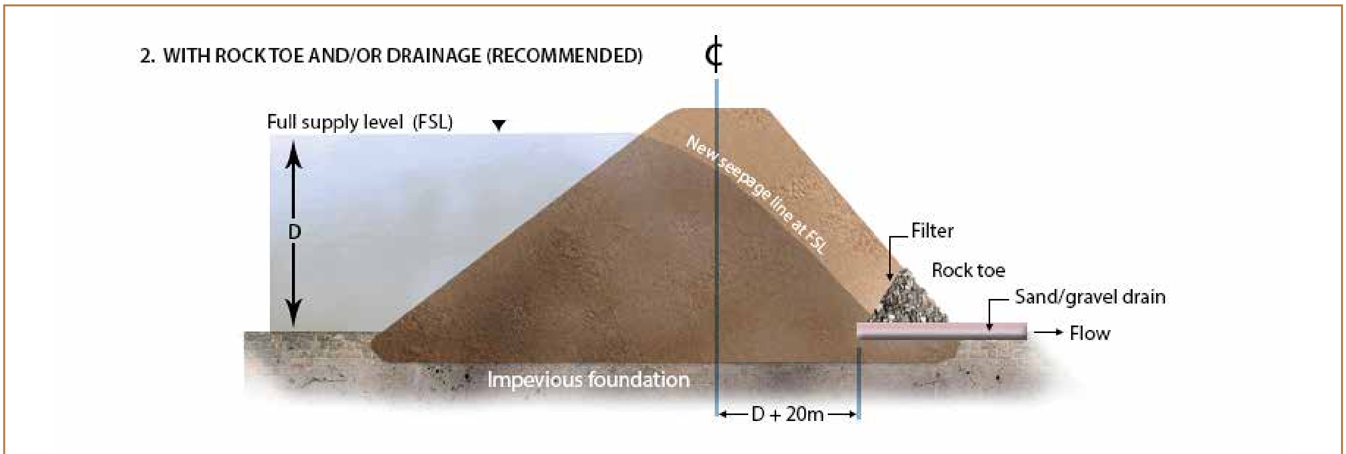


Figure 54: Small earth dam with drainage (Recommended).
Source: Pixiniti Studios.

Table 30: Advantages and disadvantages of small earth dams. Source: (Stephens, 2010; MWI, 2015; Nissen-Petersen, 2015).

Advantages	Disadvantages
• Built from locally available materials and resources: soil from borrow pits, human labour and animal power, which can be complemented with farm machinery.	• High vulnerability to evaporation and seepage losses.
	• High vulnerability to siltation: the storage capacity reduces over time, which imposes the need to correspondingly increase the storage capacity.
	• If not well designed through proper side slopes, provision of spillway, freeboards and crest height, and adequate upstream protection, an earth embankment could easily be damaged or destroyed by water flowing on, over or against it.
• Design procedures are fairly simple and straightforward.	• Inadequate compaction of the earth dam during construction may culminate in weak structural integrity, offering possible pathways for seepage or even collapse.
• Owing to their small sizes, there is no need for sophisticated equipment.	• Designing and constructing adequate spillways is usually the most technically difficult part of any dam construction works. Any site with a poor quality spillway should not be considered.
• Hydraulic forces on the embankments are low, thus foundation requirements are less stringent than for other types of dams. The base of embankments should be broad to spread the load on the foundation.	• Earth dams require continuous maintenance to prevent erosion, tree growth, subsidence, animal damage/ cross-contamination and seepage.
• Earth dams resist settlement and movement better than more rigid structures and can be more suitable for areas where earth movements are common.	• Embankments have been constructed on the principle of a solid wall of earth. If this is done properly, such homogeneous embankments are still a highly cost-efficient and reliable option. They are, however, generally inferior to the modern method of zoned construction
	• High vulnerability to cross-contamination: Catchment area is usually polluted by multivariate factors, especially organic materials from livestock, and causes general low levels of water quality.
	• High vulnerability to water-borne diseases: Due to large volumes of surface water accumulated during long periods.

8.3 Siting

The selection of a suitable site is essential before building the earth dam. This is done to ensure that the entire area from which the dam is constructed has good properties for holding water. One way to site the earth dam is using aerial photographs and measuring the hydrological conditions. Field visits may be useful once an initial selection has been made based on the assessment of the aerial photographs and hydrological conditions. For accurate siting and positioning of earth dams, a GPS system may be a useful tool.

As the small earth dam is intended to be used for small-scale irrigation, the site should be close to the application area. Considering these factors may reduce possible costs of pumping or piping the water from the earth dam. There are several other factors that need to be taken into account when assessing the feasibility of an earth dam. These are enumerated as follows (Stephens, 2010; MWI, 2015; Nissen-Petersen, 2015):

1. The size of the catchment: it should generate sufficient runoff to fill the reservoir.
2. The embankment should be situated in the narrow part of the valley.
3. The dam should be situated in a part of the valley which has a water tight floor.
4. The dam walls should comprise of impermeable rock or soils to reduce water loss through seepage.
5. The valley floor should not be too steep. This will increase the storage capacity of the dam.
6. Earth dams should be located approximately 100 m from bends in the valley to reduce erosion during heavy runoff.
7. Reservoirs should not contain boulders or rock outcrops as these may cause leakage unless covered with clay soil.

According to Stephens (2010), Google Earth Pro is an advanced measurement tool that can be used for three dimensional (3D) measurements of areas and depths or heights. These dimensions are important in pre-selection of dam sites. Google Earth Pro can be used to specifically determine the potential site for dam embankment, throwback of water and catchment for the dam. Technical viability of these sites can be authenticated after carrying out soil tests at the site.

Factors to consider for site investigation include geological conditions, stream flow and rainfall/storage reservoir characteristics of the proposed dam catchment (Stephens, 2010). Parameters to be investigated include the soil type and parent rock material. These would affect the location of the dam and materials required for its foundation, abutments (upstream and downstream slope sections), embankment (dam wall) and spillway.

Earth dams are often filled with surface runoff from upstream catchments. Therefore, the entire catchment area must be examined to establish whether the runoff has any pollution source. The earth fill should be available at the reservoir as well as the spillway areas. According to Stephens (2010), there are two categories of soils that are important in the construction of soil dams: impermeable soils (e.g. clay for damming water), and gravel materials or aggregates (for drainage).The suitability of the site of an earth dam is subject to whether the soil will hold water when compacted during the construction process. The reservoir area should preferably comprise impervious layers of clay or silty clay soils. A rule of thumb is that soil must contain at least 20% clay. Coarse soils containing sand and/or gravel are not suitable along with rocks that may contain salts. In portions of the earth dam where clay content is low, large amounts of clay may have to be transported and compacted to make it impervious. However, this may raise the cost of construction. Moreover, limestone areas are ideal for siting earth dams because they might have sinkholes just beneath the surface. Such spots may drain completely overnight.

In addition, there are three methods of checking soil suitability for earth dam construction. These are: The squeeze method, the water permeability test and the groundwater test. Each of these methods is described in Table 31.

8.4 Design

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

8.4.1 Catchment delineation and computation of catchment yield

According to Stephens (2010), after mapping the site of the dam and the catchment area, one of the methods to

Table 31: Methods to check the suitability of the soil for an earth dam.
Source: Adapted from Stephens (2010) and MWI (2015).

Method	Description
Squeeze method	Take a handful of soil and wet it with water to make it moist. Squeeze the soil with your palm. Open your palm and check the shape of the soil after squeezing. If the soil retains its shape then it's good for earth dam construction. If the soil crumbles, the site is not suitable.
Water permeability test	Dig a hole about half a metre deep and fill it with water to the top. Cut enough leaves to cover the hole. During the next day same time, check on the water level. If it has reduced owing to seepage, refill it with water up to the top. After refilling the hole with water, cover it again with leaves. If the water level is still high, this implies that the soil is impermeable and thus suitable for construction of earth dam. If the water has receded again then the site is not suitable for earth dam construction.
Groundwater test	Dig a hole that is 1 m deep. Cover this hole with leaves so as to reduce on the rate of evaporation. During the next day same time, check on the water level. If it has reduced owing to seepage, then the site is not good for earth dam construction.

calculate the capacity of the dam catchment is the soil conservation service curve number method (SCS-CN).

Thus, after identifying the site and delineating the catchment, there is a need to divide the catchment area into a maximum of five sub-catchments represented by different curve numbers. For each of the sub-catchments, namely A, it is recommended to identify and label the different land use areas as A_1, A_2 ,…, etc. More precise estimates could be made using surveying equipment (e.g. Total Stations), chaining or pacing. After determining the land use areas, the overall curve number (CN) is identified from Figure 55. Then, the weighted curve number is computed using Formulas 8 and 9.

$$A = A1 + A2 + A3 + A4 + A5 \quad \text{Formula 8}$$

> Where A is the sub-catchment.

$$CN = \frac{1}{4}[A_1(CN_1) + A_2(CN_2) + A_3(CN_3) + A_4(CN_4) + A_5(CN_5)] \quad \text{Formula 9}$$

> Where CN is the curve number.

Having determined the curve numbers, it is possible to use Formula 10 to compute the potential runoff (Q) for the catchment that would eventually flow into the earth dam (Stephens, 2010):

$$Q = \frac{(P-1)^2}{(P-1+S)} \quad \text{Formula 10}$$

> Where Q is the runoff (mm), P is the rainfall (mm) and S is the maximum recharge capacity (mm).

8.4.2 Supply-based estimation of the storage capacity

The storage capacity of the earth dam is given by Formula 11 (Stephens, 2010):

$$Q_{dam} = \frac{L x T x}{6} \quad \text{Formula 11}$$

> Where Qdam is the storage capacity (m^3) with a 20 % inaccuracy (it must be revised when the site is

Figure 55: Hydrologic Soil Group A to D. Group A soils: High infiltration (low runoff): sand, loamy sand, or sandy loam; Infiltration rate > 0.75 cm/hour when wet. Group B soils: Moderate infiltration (moderate runoff): silt loam, loam, or loamy sand; Infiltration rate 0.375 to 0.75 cm/hour when wet. Group C soils: Low infiltration (moderate to high runoff): Sandy clay loam; Infiltration rate 0.125 to 0.375 cm/hour when wet. Group D soils: Very low infiltration (high runoff): clay loam, silty clay loam, sandy clay, silty clay or clay; Infiltration rate 0 to 0.125 cm/hour when wet. Source: (MWI, 2015).

Description of land use	Hydrologic soil groups			
	A	B	C	D
Paved parking lots, roofs, driveways	98	98	98	98
Streets and roads				
Paved with curbs an storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Cultivated (agriculture crop) land*				
Without conservation treatment (no terraces)	72	81	88	91
With conservation treatment (terraces, conlours)	62	71	78	81
Pasture or range land				
Poor (< 50 % ground cover or heavily grazed)	68	79	86	89
Good (< 50 - 75 % ground cover, not heavily grazed)	39	61	74	80
Meadow (grass, no grazing, mowed for hay)	30	58	71	78
Brush (good, > 75 % ground cover)	30	48	65	73
Wood and Forests				
Poor (small trees / brush destroyed by overgrazing / burning)	45	66	77	83
Fair (grazing but not burned, some brush)	36	60	73	79
Good (no grazing, brush covers > 75 % impervious)	30	55	70	77
Open spaces (lawns, parks, golf courses, cemetries)				
Gras covers 50 % of ground	49	69	79	84
Good (gras covers 50 % of area)	39	61	74	80
Commercial & business districts (85 % impervious)	89	92	94	95
Industrial districts (72 % impervious)	81	88	91	99
Residental areas				
0.05 ha piots, about 65 % impervious	77	85	90	92
0.1 ha plots, about 38 % impervious	61	75	83	87
0.2 ha piots, about 25 % impervious	54	70	80	85
0.4 ha piots, about 20 % impervious	51	68	79	84

approved for construction), L is the length of dam wall at full supply capacity (m), T is the throwback of water (m), H is the maximum height of the earth dam (m).

8.4.3 Demand-based estimation of the storage capacity

According to Stephens (2010), this is the best way of determining the actual capacity of the earth dam. The advantage of coming up with actual size is that the cost of the dam is realistic and quite often lower than the cost of the dam based on supply design. It is recommended to use the Double Mass Curve Analysis (DOMCA) approach. However, it is required to ensure that the crop used for computing monthly and cumulative demand is one with the highest water requirements.

8.4.4 Computation of other features of the earth dam

8.4.4.1 Freeboard

This is a very important feature as it ensures that there is minimal chance of the earth dam over-topping. The earth dam overtops owing to the fact that the hydrostatic forces acting on the embankment are greater that the gravitational forces of the embankment itself. This could be precipitated by inadequate compaction during construction as well as fissures or cracks created within the embankment. Thus, the freeboard, which is the height between full supply level and the crest of the embankment, is given by Formula 12:

$$\mathbf{F = 0.021 \times (T)^{0.5}} \qquad \text{Formula 12}$$

> Where F is the freeboard (m) and T is the throwback (m).

8.4.4.2 Top width of the embankment

This is given by the formula 13:

$$\mathbf{W = \frac{H}{5} \times 1.5} \qquad \text{Formula 13}$$

> Where W is the top width of the embankment (m) and H is the total height of the embankment (m).

8.4.4.3 Slopes of embankment

For a typical design of a small earth dam, the upstream slope should be a minimum of 3:1 while the downstream slope should be a minimum of 2:1. This is necessary for erosion protection to be in place, which can be designed using a combination of small as well as large rocks.

8.4.4.4 Evaporation, seepage and siltation

Evaporation, seepage and siltation need to be considered and minimised. Table 32 shows strategies to minimise their negative effects.

8.5 Construction

A small earth dam should always be designed and supervised by an experienced and skilled engineer, because any failure could pose serious consequences. The items required for dam design include:

- Feasibility assessment reports.
- Survey and drawing equipment.

Before the construction, a topographical survey is required to precisely locate the dam wall and the spillway.

8.6 Monitoring and evaluation

Regular inspection and maintenance should be done to ensure that the earth dam remains in a good condition. Earth dams often have heights below 10 m and thus fall under lower hazard category. Such dams do not require rigorous inspection and maintenance except for the following issues:

1. Do a transect walk around the spillway and remove any logs or trees growing in the vicinity of the dam. Tree roots could crack the embankment and compromise the stability of the dam. Only grass should be allowed to grow on dam embankment.

2. Go often to the lower side of the embankment and check on the amount and quality of seepage. If seepage increases over a time and the water becomes turbid, that is an indication of internal erosion in the embankment which could lead to piping failure. If this happens, inform a qualified engineer to correct the situation.

3. Plant a at least a 5 m buffer zone of vegetation such as grass to surround the earth dam especially if there are farming activities or denuded areas in the catchment.

4. It is advisable to undertake periodical monitoring of the water quality as a safety measure of ensuring that no harmful chemicals enter the earth dam that may jeopardize the health of the environment or consumers.

5. The dam should be fenced to prevent livestock drinking directly from the water thus contaminating it or causing erosion.

In addition, Nissen-Petersen (2015) highlights key additional issues with regard to the monitoring and maintenance of earth dams, as it is shown in Table 33:

Table 32: Strategies to minimise evaporation, seepage and siltation in earth dams.
Source: (Nissen-Petersen, 2015)

Variable	Strategy
Evaporation	Evaporation needs to be taken into account and minimised by deepening the centre part of a dam reservoir as much as possible to reduce evaporation losses. Also, by making a windbreak of thorny branches and bushes along the sides of a dam reservoir. Such thorny fences can be inter-planted with cactus to function as an effective fence, keeping out unwanted people, livestock and wildlife. Evaporation losses can be further reduced by covering a water reservoir with empty and closed plastic water bottles, which float on the water surface. Although it will take many empty water bottles to cover the whole water surface of an earth dam, it requires fewer bottles to cover only the deepest part of a reservoir when the shallow parts have dried up.
Seepage	Seepage under dam walls in clay soil is stopped by ploughing the base. In sandy soil a ditch is filled with clayey soil. Seepage through dam walls can be stopped by covering the back toe of dam walls with an apron of rubble stones. Seepage through dam floors consisting of sandy soil can be reduced by a layer of clayey soil, or soil mixed with animal dung, which is compacted by livestock or a heavy vehicle driven back and forth, or by the natural siltation of fine soil particles brought in by runoff water. Seepage under earth dams can be utilized by sinking a hand-dug well, from where clean water can be drawn as it has been filtered by passing through the soil.
Siltation	Low degree of siltation is good for earth dams because it seals seepage through the floor, but if siltation is unchecked, a dam reservoir may be silted up completely within a few years, thereby leaving no storage for water. Siltation of earth dams can be prevented by constructing a series of silt traps made of scrubs, stones and/or brush wood inter-planted with vegetation disliked by livestock, in the inflow to earth dams. Silt accumulating in the silt traps must be removed.

Table 33: Monitoring and maintenance requirements of an earth dam.
Source: (Nissen-Petersen, 2015).

Spillways	Always open and clear of any obstacles that can slow down the flow and speed of surplus water flowing over the spillways, e.g. during floods. If spillways are blocked, the water level will rise, thereby rendering safety features useless, and the dam prone to washout. However, never raise the height of the spillways without an expert's advice.If raised in the wrong way, floodwater will flow over the crest and wash out a large section of the dam wall, which is costly to repair.
Freeboards	With plastic bags filled with soil along their sides, to protect the ends of dam walls from erosion by floodwater passing over the spillways. In case of flood damage to these sand bags, they must be repaired to avoid damage to the dam wall.
Crests	In places where large soil clumps were used for building the dam wall, freeboard and crest must be filled and compacted with soil.
Dam walls	Protect against livestock grazing on the batters, because livestock will erode the dam wall, thereby making the wall prone to flood damage.
Silt traps	The inflow must be maintained and the upper layer of the accumulated silt must be re-moved from the traps to avoid the water reservoir being filled up with silt.
Catchment area	Check on the catchment and assess whether there is need for afforestation and soil con-servation measures. If this is the case, mobilize the community accordingly. Ensure that trees are not planted on the earth dam wall or water pan walls. If there are any, cut them out.

9. SHALLOW GROUNDWATER RECHARGE FOR OFF-SEASON SMALL-SCALE IRRIGATION

9.1 The technology

Natural shallow groundwater recharge occurs when runoff infiltrates the ground into an underlying aquifer. This only happens when there are no impermeable surfaces such as pavements, tarmacked roads, clay layers or build-up areas. Artificial recharge is the planned human activity of increasing the amount of groundwater through works designed to increase the percolation of surface waters into shallow groundwater.

In addition to recharging shallow groundwater, there are other beneficial purposes of shallow groundwater recharge:

1. Increasing water available for agriculture.
2. Increasing soil moisture and soil fertility.
3. Decreasing runoff, flooding, erosion, and sedimentation.
4. Increasing deep groundwater levels.
5. Storing excess surface water for future use.

9.2 Siting

Table 34 shows key factors that should be considered in the selection of shallow groundwater recharge techniques.

9.3 Design and construction

There are two group of methods used for recharging shallow groundwater, namely direct and indirect techniques. Direct techniques are among the simplest and most widely applied, where runoff moves from the land surface to the shallow aquifer by means of percolation through the soil. Examples of direct surface techniques include flooding, percolation pits, infiltration trenches, water spreading weirs, check dams and groundwater dams, among others.

Direct subsurface techniques are methods for accessing deeper aquifers. These include: injection wells or recharge wells, recharge pits and shafts, dug-well recharge, borehole flooding, natural openings and cavity fillings. Such methods require less land than direct surface methods. Other direct methods involve a combination of direct surface and direct subsurface techniques that can be applied to achieve specific recharge needs. Examples include basin or percolation tanks with pit shaft or wells. In addition, indirect techniques include the installation of groundwater pumping facilities and induce infiltration in the drainage basin.

Due to their suitability for RWHI management, this chapter focuses on a selected set of direct surface techniques to increase shallow groundwater. These techniques are basically micro-catchment and/or in-situ RWH systems that can be used to directly or indirectly recharge shallow groundwater which can in turn be used for off-season small-scale irrigation, usually by means of hand-dug wells. The selected techniques are highlighted in Table 35. Figure 56 shows infiltration trenches and percolation ponds in Ethiopia as an example of practices that can be used to increase shallow groundwater levels. In addition, it is worth considering that the implementation at watershed level of surface and groundwater dams, water spreading weirs and other relevant spate irrigation techniques, and different types of check dams, among others, have been shown to recharge shallow and deep groundwater levels (Woldearegay, 2016). Similarly, by controlling sand and

Table 34: key siting factors for the selection of shallow groundwater recharge techniques.

Overall topography	Availability of land and present use: Determining if there is land that can be used for recharge. Type of top soil: Determining the capacity to absorb rainfall and feed the underlying aquifers. Presence of streams that can serve as high recharge zones.
Geologic structure and capacity of the aquifer	Transmissivity (the rate at which water flows horizontally through an aquifer). Storability (thickness of the aquifer and the amount of water that can be stored in an aquifer). Presence / absence of impermeable layers that can impede percolation (aquitards). Existing depths to water table and groundwater flow directions.
Water sources available for recharge	Amount and pattern of rainfall in the selected area. Availability of catchment areas (such as rock outcrops or road catchments). Availability of non-conventional water sources for reuse, in particular treated municipal and industrial wastewaters.
Water quality	Recharge water must meet quality standards and be chemically compatible with existing groundwater and have a suitable temperature.

gravel mining in seasonal streams, it is possible to enhance the capacity to absorb high flows and feed the surrounding aquifer systems.

The increase in groundwater levels is basically due to the direct or indirect higher infiltration of runoff as a result of the implementation of these technologies. Further, these type of natural recharge technologies inherently increase the soil moisture in the crop rooting zone during wet periods, induce capillary rise causing water to rise into the root zone during colder dry periods and contribute fixating nitrogen to the soil. Thereby, potentially enhancing off-season irrigation during dry periods. At a larger scale, effective watershed management technologies and practices, among them, upper catchment treatment practices, early treatment of gullies and minimization of gully heads, and rehabilitation of affected areas through simple, cheap, flexible and local available materials, are interventions that increase groundwater levels, and in turn, enhance RWHI management.

Figure 56: Infiltration trenches (left) and a percolation pond (right) in Ethiopia.
Photos: K. Woldearegay and MetaMeta.

Table 35: Overview of technologies and practices that can be used for shallow groundwater recharge.
Source: (Knoop et al., 2012).

Types	Key function	Land Use	Slope	Soil		Complementary technologies	Constraints
Contour bunds: Level soil bunds, Fanya chini	Soil moisture storage.	Usually Cultivated.	Maximum 20 %.	All soils except heavy black cotton soils.		Trenches of moisture and soil conservation is needed; need stabilized with suitable grass / legume for forage – also making it productive; maintenance according to fanya juu principle for quick benching.	Compared to stone bunds they take more land; requires regular maintenance; the benching speed is low b / c deposited soil in the upper channel is removed for maintaining and upgrading the bund; too close spacing takes up land.
Contour bunds: Graded soil bunds	Soil moisture storage.	Cultivated land.	Maximum 20 %.	All soils except heavy black cotton soils.		Graded is in high rainfall areas or for soils with poor infiltration; need to be stabilized with suitable grass / legume for forage - also making it productive; cut and carry of the grass / legume than free grazing.	The gradient is sensitive and difficult to maintain it. When small there is water logging and when large erosion / scouring occurs. Integration With waterways is a must.
Contour bunds: Level fanya juu	Soil moisture storage.	Cultivated.	Maximum 15 %.	Deep soil.		Trenches if moisture and soil conservations is needed; need to be stabilized with suitable grass / legume for forage – also making it productive; cut and carry of the grass/legume than free grazing.	Not possible on steep slopes; cannot be crossed by livestock; more labour b/c throwing the soil up; close spacing takes up land.
Contour bunds: Graded fanya juu	Soil moisture storage.	Cultivated.	Maximum 15 %.	Deep soil.		Biological stabilization; fodder source; integration with a waterway is a must.	With a maximum gradient of 1 % discharges excess runoff generated from the inter terrace spaces to the adjoining natural or artificial waterway at a non-erosive velocity. Vertical intervals: flexible and quality oriented approach. • Slope 3 - 8 % VI = 1-1.5 m • Slope 8 -15 % VI = 1-2 m Layout along the contours but is 1 % gradient using line level – discuss spacing with farmers.
Contour bunds: Stone, trapezoidal and soil bunds.	Soil moisture storage.	All land uses.	In all slopes.	All soils.		Is also good for destoning fields; the stone takes less space compared to soil bunds and fanya juu.	In low temperature areas could harbour rodents; frequent maintenance and attendance needed as it cannot be stabilized with plants; need to stop free movement of livestock.

Table 35 (cont.): Overview of technologies and practices that can be used for shallow groundwater recharge.
Source: (Knoop et al., 2012).

Types	Key function	Land Use	Slope	Soil		Complementary technologies	Constraints
Cut-off drains	Soil moisture storage.	In all land uses but constructed between two different land uses or slope breaks.	0.5 to 1 % gradient (but done across al the natural slopes).	All soils.		Stabilizing the embankment / dike with plants; apron or drop structure is needed at the outlet; expert / engineer designed – need estimation of peak runoff.	Erosion risk at the outlet due to improper attention for provision of drop structures.
Waterways	Soil moisture storage.	Along the natural or artificial waterway (can be constructed by adjoining mix of one or more land uses).	All slopes because it follows natural slope.	All soils.		The channel bed and the side should be stabilized with vegetation; pitching required depending on slope and vegetation cover. For higher slope drop structures are needed.	No limitation, however, on artificially constructed one more stabilization effort is needed.
Grass strips	Soil moisture storage.	All land uses.	Gentle slopes up to 8 %.	All soils.		Sterile grass that do not expand sideways is required.	Not used on steeper slopes; farmers reluctant to leave a strip of land.
Gully plugging	Soil moisture storage.	All land uses.	All slopes.	All soils.		Biological Stabilization is a must; area closure of fencing; maintenance; benefit sharing mechanism as usually gullies are located either at boundaries or communal ownership.	Need of upper Catchment treatment is a must; it is heavy investment requiring huge labour.
Terracing: Bench terracing.	Soil moisture storage.	Cultivated fields and unused steep hillsides.	On average 12 - 58 % Considering the various land use types.	Deep soils.		Bank stabilization inward; outward sloping depending on runoff; good for perennial crops on steep slopes.	Heavy labour.
Terracing: Hillside terracing.	Soil moisture storage.	On degraded lands; forest lands; grazing lands; communal grazing lands.	Steep hillsides (20 - 50 %).	Shallow soils usually <50 cm depth.		Can be combined with trenches for maximum runoff harvesting; b / n terraces pitting and planting; area closure; avoid free grazing and cut and carry.	Heavy labour; area closure is a must.
Tied ridges, Demi lunes	Soil moisture storage.	Cultivated lands.	Gentle Slopes.	Loamy soils with good water holding capacity; not good on sandy soils.		Good for row crops between the furrows.	Unless contoured can be easily overtopped. Used on gentle slopes and flat lands only.
Percolation ponds and contour trenches	Shallow groundwater recharge.	Degraded hillsides.	Maximum of 100 %.	Soils of good Infiltration need some 50 cm of top soil to be applied.		Can be combined with other measures such as hillside terraces, stone bunds, and trenches based upon soil, slope and stoniness, and also in large gully areas for tree planting.	Labour Intensive.

10. OFF-SEASON SMALL-SCALE IRRIGATION SYSTEMS

Off-season small-scale irrigation is a group of technologies operated and managed by individuals or in small self-initiated groups, which usually have been initiated and funded by the farmers themselves in areas lower than 2 ha, and that use low-cost and easy-to-maintain technologies in order to grow high-value crops during dry periods for direct consumption and/or the local market (De Fraiture and Giordano, 2014).

Key factors that determine the success of an off-season small-scale irrigation system are (Ngigi, 2009):

1. The irrigation system, i.e. water lifting and application technology.
2. Farmers' participation, skills and capacity.
3. Type of water source.
4. Type of crop.
5. Market demands and accessibility.
6. Provision of back-up services to sustain production.

This chapter intends to give basic information and know-how with regard to pumping systems on one hand, and water application systems on the other, as these systems can be used in combination to facilitate off-season small-scale irrigation. Additional information and know-how can be found as part of the Sustainable Sanitation and Water Management Toolbox in the section "Optimisation of Water Use in Agriculture" at **http://www.sswm.info/category/implementation-tools/water-use#**. The toolbox also includes a detailed list of scientific references and technical reports which are accessible directly on the toolbox.

10.1 Water pumping systems

Several types of energy sources exist for delivering or operating water pumps for off-season small-scale irrigation. Thus, pumps are usually categorised according to the energy use to lift the water, i.e. manual pumps or mechanised pumps (gravity-fed, animal-powered, solar, wind, electric, petrol/diesel pumps).

Table 36 provides an overview of key factors relevant for the implementation of pumping systems. Xie et al. (2014) found that the area expansion potential in sub-Saharan Africa is 30 million ha for motor pumps and 24 million ha for treadle pumps, which is a specific type of manual pump. These systems can benefit between 113 and 369 million rural people in the region generating net revenues of USD 14–22 billion per year, depending on the specific type of system (Xie et al., 2014).

Further, pumps can be classified according to mechanical principles as reciprocating, rotary, axial-flow, centrifugal and airlift (IRC, 1987). Table 37 provides the mechanical selection criteria and characteristics of different types of pumps. In addition, it is important to consider that the performance of a pump varies depending on the water discharge (i.e. how much water the pump is moving) and the pumping head (i.e. the pressure produced).

10.2 Manual pumping

A manual pumping system is any simple device powered by human power (i.e. hand or foot) (Bruni and Spuhler, 2010a). Low-cost lifting devices such as a bucket and rope or windlasses are usually used by small communities or individual households. Thus, small-scale irrigation has traditionally been fed through the arduous lift-and-bucket method, which requires high physical input and limited well-depth. Further, different types of hand pumps (e.g. (the rope and washer pump) are in use in sub-Saharan Africa for lifting water from shallow boreholes (up to 60 m) and hand-dug shallow wells for small-scale irrigation

Table 36: Key factors relevant for the implementation of small-scale surface pumping systems. Source: adapted from Bruni and Spuhler (2010a,b).

System	Description	Advantages	Disadvantages	Costs	Suitability
Manual pumping	Water-lifting devices that can be operated manually.	Simple to install and operate. Effective: depths up to 60 m. Versitability. Suitable to a wide range of local conditions.	High maintenance requirements, especially at community level. Low cultural acceptance.	Low-cost options exist making use of locally available materials and labour.	Arid and semi-arid areas for small-scale irrigation at household level. Highly suitable for places where access to power sources is limited and where financial resources for investment are constrained.
Mechanised pumping	Water-lifting is driven by various non-manual power sources.	Very high performance if correctly maintained and operated.	High level of technical skills. Regular need for spare parts.	High/medium capital, operation and maintenance costs. Low-cost options for mechanised pumps are not abundant.	Arid and semi-arid areas for small-scale irrigation at community level. Medium suitability for individual small-holders.

Table 37: Characteristics of different types of pumps. Source: (IRC, 1987).

Type of pumps	Pumping depth	Characteristics and Applicability
Reciprocating (plunger)	Up to 7 m.	- Low speed of operations. - Hand, wind, or motor powered; efficiency low (25-60 %). - Capacity range: 10-50 l/min. - Suitable to pump against variable heads. - Valves as cup seals require maintenance attention.
Rotary (positive displacement) a. Chain and bucket pump b. Helical rotor	 Up to 10 m. 25-150 m (usually submerged).	- Low speed of operation. - Hand, animal or wind powered. - Capacity range: 5-30 l/min - Discharge constant under variable heads. - Good efficiency, and hence best suited to low-capacity high-lift pumping.
Axial-flow	5-10 m.	- High-capacity low-lift pumping. - Can pump water containing sand or silt.
Centrifugal a. Single-stage b. Multi-stage (shaft driven) c. Multi-stage submersible	Up to 7 m. 20-35 m. 25-50 m. >30 m.	- High speed of operation: Smooth/even discharge. - Efficiency range 50-85% depending on operation speed and pumping head. - Requires skilled maintenance. - Not suitable for hand operation; powered by engine or electric motor. - As for single stage. - Motor accessible above ground. - Alignment and lubrication of shaft critical; capacity range 25-10,000 l/min. - As for multi-stage shaft-driven. - Smoother operation, maintenance difficult: repair to motor or pump requires pulling unit from the well. - Wide range of capacities and heads. - Subject to rapid wear when sandy water is pumped.
Air lift	15-50 m	- High capacity at low lift. - Very low efficiency especially at greater lifts. - No moving parts in the well. - Well casing straightness not critical.

purposes (Akvo, 2015b). Innovative manual pumps are currently under development (e.g., Afripump/BluePump, with a life span of 25 years with low maintenance requirements) (van Beers, 2008).

Most manual pumps are positive displacement pumps and have reciprocating pistons or plungers. The water is lifted by a piston that is raised and lowered inside a cylinder that has a foot-valve. The piston (or plunger) is moved by a pump rod connected directly to a T-handle or a lever handle at the pump head. In some types, a flywheel with crankshaft is used to create the reciprocating movement of the piston.

The capital costs are generally low, and the discharge is also relatively low. However, their use is suitable for small-scale irrigation. If the farm size is large, the hand pumps may not be applicable due to the limited discharge capacity especially considering that the pumps are manual systems that are operated by humans.

A system which shows high performance and suitability is a treadle pump (IPTRID, 2000; Kay and Brabben, 2000). The system comes from a basic adaptation of the hand pump with the transfer of power supply to the feet where increased power generation can be supplied (Kay and Brabben, 2000). Using low physical input and capital, the treadle pump outperforms traditional methods by lifting 7 m^3/h from wells (conventionally up to 7 m deep) and surface water. For treadle pumps and micro-irrigation systems, the performance is encouraging. Further, a treadle pump can be produced locally at relatively low costs ranging from USD 50 to USD 120 motorised pumps often cost over USD 300) and have been shown to increase income by over USD 100 per season (Postel, 2001). Also, treadle pumps can provide as much as an eightfold increase in irrigation capacity on small-scale irrigation schemes (FAO, 2001). However, traditional limiting factors of the treadle pump include accessibility (i.e. costs are not within the farmers' means in many areas) (Ngigi, 2009), labour, scale, limited crop use, and water depths lower than 7 m (FAO, 2001).

10.2.1 Rope and washer pump

Figure 57 shows a rope and washer pump. This is a pump with a rope tied in a loop through a PVC pipe and a rope guide. The pump is used for drawing water from ponds, shallow wells, underground tanks or any other reservoirs whose depths usually range from 11 m to 60 m. The rope and washer pump is composed of the following components; nylon rope, rubber washers, rope guide and pulley wheel.

The rope and washer pump can be oriented either vertically, as in the case of a well, or inclined parallel to one of the sides of a trapezoidal pond. In order to operate the rope-and-washer pump, the direction of wheel rotation depends on which side the cranking handle is placed in relation to the pond. If the operator is standing on the right side of the wheel while facing the pond, the handle will be cranked clock-wise. However, if the operator is standing on the left side of the wheel while facing the pond, the handle will be cranked anti-clock-wise. Given that most people are right handed, it is recommended to place the cranking handle on the right side so that it is operated clockwise.

Further, in the initial rotation of the handle, the first washer to enter the riser pipe fits a column of water as it is pulled upwards given the force of cranking by the operator. However, since there is space between the washer and the riser pipe, some water will escape and fall in the space where a column of water is held and lifted by the second washer. This explains why it takes a number of rotations before water starts flowing from the spout. When the space between the washers increases due to abrasion and tear, it requires more effort to lift the water column given that a lot of it will escape backwards. In such a case, the washers should be replaced. Figure 58 shows a rope and washer pump being operated.

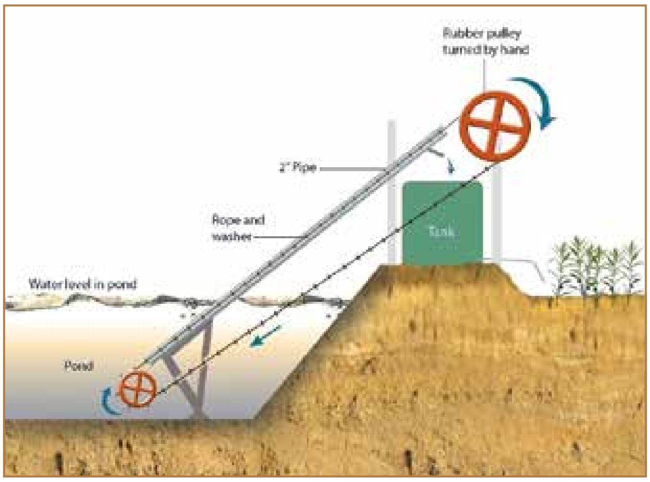


Figure 57: The rope and washer pump.
Source: Pixiniti Studios

10.2.2 The Brazilian Pump

The Brazilian pump (Figure 59) is an improvised version of the rope-and-washer pump or the hip pump (section 10.2.3). The stroking movement of the handles (whether through cranking or back and forth motions) draws the rope and washer or the piston upwards. This creates a vacuum in the chamber that results in suction of water from the pond along the inlet pipe. Just before this water is released to the delivery pipe, some of it enters a 1.5 L plastic bottle. During the movement that pushes the piston inwards, pressure is created in the bottle. This pressure increases with continued push of the piston inwards. The result is a counter-pressure along the outlet pipe that culminates in the discharge of water to very high heads. Such pressure can be used for sprinkler or drip irrigation.

10.2.3 The Money Maker pumps

In eastern and southern Africa, Kickstart has been distributing two models of treadle pumps: the Super Moneymaker Pump (SMP) and the Moneymaker Hip Pump (MHP). Thus, at costs of USD 100, the SMP can pump water from a source up to 10 m in depth and pressurize water up to

Figure 58: Operation of the rope and washer pump. Photo: A. Oduor.

13 m, and can irrigate about 0.75 ha using a hose length over 330 m (Akvo, 2016b). In addition, the MHP was developed to create a lower cost (USD 35) portable pump. The MHP pump is a modified treadle pump which the user operates through a rocking motion (Haskins, 2008). It is light (4.5 kg) and can irrigate 0.4 ha. Like the SMP, the MHP can pull water from 7 m and push water an additional 14 m above the pump. The adoption of MHP is growing fast, and over 16,000 units were sold by 2008 (Kinaga, 2008). The money-maker pumps are ideal for pumping water from on-farm ponds into a drip irrigation system (Figure 60) or from small earth dams into the cropland.

Figure 59: An improvised Brazilian hip pump with an inclusion of a plastic bottle. Photo: A. Oduor.

10.3 Mechanised pumping systems

10.3.1 Gravity-fed irrigation

Gravity is a reliable, low-cost and renewable energy source for off-season small-scale irrigation systems. However, it strictly depends on the topographical location of the RWHI system relative to the crop application area. Most smallholder irrigation schemes in sub-Saharan Africa are gravity-fed with the conveyance system being unlined/lined canals or pipes that deliver water from the source to the point of use. The water application can be carried using surface systems (furrows and bunds) or pressurized irrigation technologies (sprinkler and drip irrigation). Pumps that use free energy from either the flow of water or water head to lift water should be considered due to the energy costs of other types of pumping systems (Ngigi, 2009). Table 38 shows key factors relevant for the implementation of gravity-fed surface irrigation systems.

10.3.2 Animal-powered

Animal power (especially bullocks and donkeys) can be used for lifting water from large-diameter open wells where the animals pull rotating circular sweeps or push treadmills (IRC, 1987). Such animal-operated pumps require gears and slow moving, large displacement pumps. Ox-drawn bowsers mounted on wheels can also be used for small-scale irrigation. The water bowsers are fitted with a tap on which a flexible pipe can be fitted. Water is conveyed to the fields by use of the pipes.

10.3.3 Solar pumping

Solar-powered pumps are increasingly being promoted in sub-Saharan Africa (De Trincheria et al., 2016a). Solar-powered photovoltaic pumps (PVPs) have the potential to promote rural development by simultaneously delivering a reliable water source while reducing dependence on non-renewable energy sources.

However, the first consideration in evaluating the feasibility of solar water pumping systems, beyond the ability to meet the water demand, is costs. Thus, PVPs generally require high initial capital investments. Yet, PVPs show high cost-effectivity and provide greater water supply efficiency often with lower maintenance costs (van Campen et al., 2000). Further, both alternating current and direct current PVPs are more economically efficient for small-scale applications than diesel or gasoline pumping systems. Furthermore, PV/fuel hybrid systems allow a safety net for use during days with excessive cloud cover. However, solar pumps are delicate and their operation and maintenance requirements may be beyond the capacity of rural communities in many cases. Also, cases of vandalism (stealing of solar panels) have been widely reported.

With careful planning and proper implementation, PVP systems have proven successful. In the Kalale District of Benin, for example, the Solar Electric Light Fund has

Figure 60: Hip-pump (left) for lifting water from a farm pond into a drip irrigation system (right) in Makueni, Kenya.
Photos: S. Ngigi.

Table 38: Key factors relevant for the implementation of gravity-fed irrigation systems.
Source: adapted from Staufer and Spuhler (2010b).

System	Description	Advantages	Disadvantages	Costs	Suitability
Gravity-fed surface irrigation	Water is distributed by gravity over the surface of the field.	Simple. High performance. No pumping requirements. High acceptability. Low salinity risks.	Levelling requirements. High labour input. Pounding risk. Evaporation risks.	If topography is uneven, capital costs are high.	Moderate suitability to arid and semi-arid areas. Appropriate for small-scale irrigation at household level.

implemented a series of micro-irrigation systems that provide between 19 m³ L and 30 m³ L of water per day for storage and use during dry periods. In a related study, Omer (2001) found that approximately 250 PVPs have been fully installed at a cost of roughly USD 6,000 per pump in Sudan. These systems were most effective in supplying drip irrigation systems for horticulture production rather than larger cereal crop production. Thus, if both the technical and socio-economic factors are accounted for in the implementation of such systems, the PVP technology has advanced to the point where these systems can provide significant advances in sustainable rural development (Short and Thompson, 2003).

In addition, an innovative battery-less solar PVP irrigation system has been developed and implemented in northern Senegal (SEL, 2015). The centralised 6.8 kW solar array provides distributed 3-phase AC power to seven horticulture farmers that have their own shallow wells and 1-HP AC pumps. The pre-paid smart-control system distributes energy to individual pumps as it becomes available throughout the day, enabling the system to meet irrigation demands without the high capital and recurring costs of battery storage. Thus, the pay-as-you-go metering aspect allows capital costs to be recovered over time, reducing the initial investment hurdle for the farmer. In addition, the pre-paid system ensures transparency and accountability for the farmers and the operator, and generates revenue from day one to cover operation and maintenance costs. Collecting payment up front eliminates non-revenue water issues that plague typical unmetered solar irrigation systems. Shifting away from gasoline-based pumping protects farmers from volatile fuel prices and reduces carbon emissions and the risks of environmental pollution from fuel spills and leakages (SEL, 2015). Table 39 gives some of the benefits of the shared solar PV irrigation system.

10.3.4 Wind-powered pumps

Wind-powered pumps have been tested in West Africa for small-scale irrigation projects in rural remote areas (Ngigi, 2009). In addition, wind-based water pumps have been in use in some parts of Kenya since colonial times. However, windmills should be used with submersible water pumps. Therefore, their applicability for RWHI systems is limited. Further, a drawback of this system is the availability of wind with sufficient speed to turn/rotate the turbine. Wind speed measurements undertaken by Tumbulto (2005) in Accra (Ghana) confirmed that wind speeds are are often too low to run wind generators. The maintenance and operation requirements of such technologies is high and the required know-how is now widely available. However, a number of private companies are already manufacturing wind pumps in sub-Saharan Africa, e.g. in Kenya (Thika) and Senegal (Thiès), which also supply pumps to neighbouring countries (Ngigi, 2009).

According to IRC (1987), the use of wind power for pumping water is feasible if:

Table 39: Advantages of the shared solar PVP irrigation system.
Source: (SEL, 2015).

Advantages	
Fuel and time savings	Farmers typically spend USD 2 per day on fuel for gasoline-powered irrigation pumps. These pumps are over-sized and consume more fuel than necessary. Properly sized AC pumps require less energy to meet the same crop water requirements. A "pay-as-you-go" model makes solar PV more affordable for small-scale farmers.
Carbon reductions	The gas-powered pumps produce approximately 2.4 kg of CO_2/L of gasoline, i.e. 0.45 tons of CO_2 in a typical 100-day season per farmer. Additionally, fuel spills are common. Switching to solar can eliminate both sources of pollution.
Grid compatible AC pumps	AC pumps are cheaper and more readily available on the local market than DC pumps and they can be integrated with the national grid when/if it arrives. Unlike DC, not only are AC pumps compatible with a future grid connection, but excess AC power can be made a potential and profitable energy supply for domestic and commercial customers, who use AC versus DC appliances.
Distribution of electricity to decentralized pumps	Centralized electricity production, with decentralized distribution allows farmers to retain autonomy of their own wells and pumps, and creates a model for micro-utilities that can be scaled up beyond irrigation to meet other demands.
Battery-less systems	The system is built without the need for a battery to keep capital and recurring costs low.

1. Wind of at least 2.5-3 m/s are present at reliability of more than 60%.
2. The water source can be pumped continuously without excessive drawdown.
3. Storage is provided for at least 3 days' water demand to cater for wind fluctuations.

The most common type of wind-powered pump is the slow-running wind wheel driving a piston pump. The wind wheels range in diameter from 2-6 m. Modern windmills are designed to ensure that they can automatically turn on and start pumping when the wind speed is 2.5-3 m/s on one hand, and turn off when wind is excessive (i.e. more than 13-15 m/s) in order to avoid damage of the system on the other (IRC, 1987).

10.3.5 Petrol/diesel-powered portable and stationary pumps

De Fraiture and Giordano (2014) found that the adoption of water pumps which are coupled to diesel- and petrol-powered engines in sub-Saharan Africa has only recently started to take off, but the technology is spreading steadily. In Ethiopia, a conservative estimate of 400,000 pumps were imported from 2002 to 2012.

Petrol/diesel pumps can be operated independently at remote sites, and hence they are appropriate for RWHI systems. As RWHI mainly require low lifts systems, petrol/diesel engines can be used to drive reciprocating plunger pumps and centrifugal pumps (IRC, 1987) but still achieve the required lift. Small and efficient motor pumps refer to diesel or kerosene fuelled motor pumps that have a typical size between 0.5 and 2.5 HP, and have been optimized to use as little fuel as possible (Akvo, 2016a). In addition, proper motor pump selection can reduce fuel consumption significantly, which can lead to significant cost reduction.

Innovative cost-efficient irrigation pumps are available in the market for less than 100 USD depending on size and capacity. Chinese 4 HP diesel-pumps pump 20-30 L/s and can irrigate 5 ha up to heads of 6 m, consuming 0.45 L of fuel/h (Akvo, 2016a). A 1.5 HP model pumps 2-4 L/s and consumes less than 0.3 L of gasoline/h (Akvo, 2016a).

Diesel/petrol pumps can supply water under pressure in PVC/PE pipes or lay flat hoses directly connected to the outlet of the pump for the water needs of vegetables and/or fruit crops. As in most countries kerosene is widely available and cheaper than petrol, it is possible to modify the motor to run on kerosene fuel instead of petrol. For example, tests in Madagascar have shown a reduction of the running cost of 25% with kerosene and a reduction of 60% of the running costs in comparison with a petrol pump-set available on the local market (Akvo, 2016a). However, capital and operation and maintenance costs are high, especially for rural smallholder farmers. This problem is compounded by lack of spare parts and support services (Ngigi, 2009).

10.3.6 Electric pumps

In areas with reliable and stable electricity, electric pumps generally need less maintenance and are more reliable than petrol/diesel pumps (IRC, 1987). However, their applicability for smallholder farmers is limited due to numerous power fluctuations and low electricity connectivity in rural areas. However, for farmers with access to electricity, small electric pumps with motors ranging in power from 0.5 - 2 HP are adequate.

Most small electric pumps are centrifugal, which uses an impeller/propeller to spin the water rapidly. The spinning action moves the water through the pump by means of centrifugal force. Centrifugal pumps may be single or multi-stage, which means that they can have more than one impeller and casing, and the water is passed from one impeller to another with an increase in pressure occurring each time. All centrifugal pumps must have a "wet inlet", that is, there must be water in both the intake (inlet) pipe and the casing when the pump is started. Also, the pump must be primed by adding water to the intake pipe and case. Further, centrifugal pumps installed above the water level are the most commonly used type and they offer a wide range of capacities while providing a fairly constant flow rate. They are economical, although their efficiency and capacity may be limited compared to other pump types as it shown in Table 40.

10.4 Irrigation water application systems

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 irrigation system. Thus, irrigation efficiency can be divided into two components: water losses and uniformity of application. Even though water application efficiency varies greatly with the irrigation system type, Table 41 gives an indication of the efficiency related to different water application systems. In addition, the most widely practiced methods of irrigation in Ethiopia, Kenya, Mozambique and Zimbabwe are summarised in Table 42.

10.4.1 Conventional drip irrigation systems

According to Stauffer (2010), drip irrigation is a technique in which water flows through a filter into special drip pipes, with emitters located at different spacing. The water is distributed through the emitters directly into the soil near the roots through a special slow-release device.

Table 40: Comparison of centrifugal pumps with other type of pumps.
Source: (HD, 2016).

Pump Type	Benefits	Points to Consider
Propeller	Simple construction. Don't need to be primed. Portable.	Cannot generate suction to lift water. Provide low energy output.
Submersible	Enclosed impellers maximize. High efficiency. Don't need to be primed. Easy to install.	Most suitable at larger depths (> 30 meter). May be less economical. Ideal for booster applications. Can only be powered by electricity. Susceptible to lightning strikes.
Centrifugal	Economical. Easy to install. Constant flow rate. Offer a wide range of different capacities.	Work up to lift of 7 m - 9 m. Need to be primed. Must be located fairly close to the surface of water supply. Losing prime may result in pump damage.
Turbine / Jet	Operate quietly. Don't need to be primed. May be used in wells. May be used in conditions where water depth changes.	Less economical. May be more difficult to install, maintain and repair. Require periodic impeller adjustments to maintain efficiency.

Table 41: Typical water application efficiencies for different irrigation technologies.
Source: (FAO, 2001).

Irrigation methods	Field application efficiency
Surface irrigation (border, furrow, basin)	60 %
Sprinkler irrigation	75 %
Drip irrigation	90 %

Table 42: Distribution of small-scale irrigation technologies commonly practiced. Distribution: High (+++), Medium (++), Low (+).
Source: adapted from De Trincheria et al. (2016a).

Small scale RWHI Technology	Ethiopia	Kenya	Mozambique	Zimbabwe
Watering can / bucket	+ + +	+ + +	+ + +	+ + +
Sprinkler system (single drag hose)	+	+	+	+
Drag Hose irrigation (no sprinklers)	+	+	+	+
Low-Cost drip irrigation kits	+	+	+	+
Ox-drawn/tractor-drawn bowsers	-	-	-	+ +
Surface irrigation	+ +	+	+	+ +
Manual pumping	+ +	+ +	+ +	+ +
Mechanised pumping	+	+	+	+

A key advantage of drip irrigation is that evaporation losses are greatly reduced (reduction of evaporation surface) (Stauffer, 2010). Further, water is more precisely applied to the plant roots as compared to other irrigation systems (drip irrigation is the most efficient irrigation system in terms of water productivity) (Stauffer, 2010). Thus, FAO (2001) found that, in most cases, switching from furrow or sprinkler irrigation systems to drip irrigation reduced water consumption by 30-60%. Drip irrigation systems, especially low-head systems can increase water use efficiency by at least 80% (Smajstrla et al., 1991; Ngigi, 2008a). Further, drip irrigation has been shown to reduce diseases that are spread through irrigation (Stauffer, 2010), and minimise weed growth and interruptions of land operations (e.g. tillage, weeding, harvesting).

One common problem with drip irrigation systems is clogging of the openings that deliver water to the crops. This clogging may come from physical, chemical or biological causes. The most common physical causes are soil particles in the field especially from surface water or other particles that are too large to pass through the drip system openings. With regard to biological causes, drip irrigation systems usually provide a conducive environment for bacteria, fungi and algae growth that eventually leads to slime accumulation in the systems. Further, chemical causes are mainly brought about by factors such as mineral precipitation as a result of low mineral solubility which usually depend on the water temperature, pH, redox potential and the concentration of the mineral elements that are present in the water. Care should therefore always be taken against clogging through water filtration, treatment, and prevention of sedimentation, among others.

Drip irrigation is usually used in farms and greenhouses especially for horticultural production. These systems commonly present various drip line sizes (8-16 mm), emitter spacing (15-60 cm), and operating pressure (low-head <2 m and high pressure up to 10 m). Button drippers, which are fixed on polyethylene pipes of 16-20 mm diameter are used mainly for orchard crops with various spacing as per fruit variety specifications. Table 43 shows an overview of strengths and weaknesses of conventional drip irrigation systems.

10.4.2 Low-cost drip irrigation systems

Contrary to conventional drip irrigation systems, simple self-made systems can be low-cost but still highly efficient (Stauffer, 2010). This type of irrigation systems are usually referred to as micro-irrigation systems and involve low-head low-cost drip (LHLCD) irrigation kits for smallholder farmers, mainly for vegetable production (Figure 63). LHLCD kits range from 20-L bucket kits (Figure 61) to 200-L drums or mini-tank systems (Figure 62) and operate at 0.5-1.0 m water head. Larger systems that can irrigate from 1,000-2,000 m^2 up to 4,000 m^2 are also available (Ngigi, 2008a).

Several types of LHLCD irrigation systems are in use in many parts of SSA (Chapin, 1996; Sijali 2001; Ngigi, 2008a,b; Sijali and Kaburu, 2008), and their costs usually range from USD 20 to USD 200 (for bucket and drum kits, respectively). However, the rate of adoption of drip irrigation is very low in sub-Saharan Africa mainly due to poor accessibility and inadequate awareness/lack of promotion among smallholder farmers. However, in eastern and southern Africa remarkable progress has been made. For example, in Koraro, Tigray (Ethiopia), shifting from surface irrigation to drip irrigation has increased irrigable area by 200% and improved irrigation efficiency from 25% to 75% (Ngigi, 2009). Table 44 shows a summary of the key factors relevant for the implementation of low-cost drip irrigation systems.

LHLCD irrigation is one of the complementary technologies for RWHI systems due to size flexibility and simplicity (in installation, operation and maintenance), which makes it suitable for smallholder farmers. Water from the RWHI storage reservoirs can be lifted by simple hand-pumps or small petrol/diesel pumps into the drip irrigation supply tank at 1-2 m above the ground. The typical LHLCD irrigation system has simple operation procedures determined by the volume of the water supply tank, which is synchronized with daily crop water demands. For example, a 200-L kit is filled twice per day, early in the morning and late in the evening in order to reduce evaporation losses. Additional irrigation water may be applied when it is too hot based on crop growth stage. This implies on average 400 L and 600 L of water application per day under normal and extreme conditions respectively.

Table 43: Advantages and disadvantages of conventional drip irrigation technology.
Source: (Ngigi, 2008b).

Advantages	Disadvantages
More efficient use of available water: Precise water application with drip irrigation is possible making irrigation much more efficient, an attribute that makes the drip irrigation method especially attractive if water is scarce or expensive. Direct evaporation from the soil surface and water uptake by weeds is reduced by not wetting the entire soil surface between rows or trees. Drip irrigation can reduce or eliminate runoff and deep percolation, making it possible to manage difficult soils from crusting to sandy soils.	**High cost:** Conventional drip irrigation systems typically cost USD 3500 - 7000 / ha, or slightly more if installed in East Africa. However, recent advances have introduced some adaptations in the systems that are making them accessible to small-scale farmers. A simple low-cost drip irrigation system would cost a farmer USD 20 to cover 15 m^2 (bucket kit), or USD 200 - 400 for a bigger system covering 250-500 m^2.
Reduced costs for fertilizer and other chemicals: Precise application of nutrients is possible using drip irrigation. Fertilizer costs and nitrate losses can be reduced considerably when the fertilizer is applied through the irrigation water (termed fertigation). Nutrient application can be better timed to coincide with plant needs since dressing can be carried out frequently in small amounts, and fertilizers are brought to the immediate vicinity of the active roots. Besides fertilizers, other water additives such as herbicides, insecticides and fungicides can be supplied to improve crop production.	**Technical limitations:** A higher level of design, management and maintenance is required with drip irrigation than other methods. Good water management under drip irrigation is essential as irrigating with more water than the plants require will result in the loss of most of the benefits of drip irrigation. Over-irrigation will also make the soil excessively wet and therefore promote disease, weed growth and nutrient leaching. However, smallholder farmers generally are quick to learn and adopt drip irrigation technology in the light of their practical experiences in using the various methods.
More uniform and higher crop yields: With a drip irrigation system, irrigation takes place on a frequent basis, enabling the water user to maintain the soil moisture at an optimum level. A well-designed, well-maintained drip irrigation system can also apply water more evenly than other irrigation methods. These features lead to more uniform and higher crop yields per land unit.	**Clogging of emitters:** Clogging of emitters is the most serious problem associated with drip irrigation. Clogging causes poor water distribution along the drip laterals and this affects plant growth. Research has resulted in the development of emitters with specific properties that minimize the opportunity for clogging. To prevent blockage, care should be taken to filter the water properly before use, depending on the particular particle size and type of suspended material contained in the irrigation water.
Reduced labour costs: Cultural practices such as weeding can be performed when the plants are being irrigated. A drip irrigation system can be automated so that water is automatically switched on to irrigate and automatically turned off after the pre-set depth of irrigation has been attained. Labour and operational costs can be reduced by simultaneous application of water, fertilizer, herbicide, insecticide or other additives through the drip system.	**Restricted root zone:** Particularly in regions of low rainfall, plant root activity is limited to the soil zone wetted by the drip emitters – usually a much smaller soil volume than that wetted by full-coverage sprinkler or surface irrigation systems. Thus, if a drip irrigation installation fails, the crops will suffer even more from drought than crops watered by sprinkler or surface irrigation. This is because under drip irrigation the confinement of roots to a relatively shallow profile means less available soil water storage for the plants.
Low energy requirements: A drip irrigation system requires less energy than a conventional pressurized system as it increases irrigation efficiency and therefore requires less water to be pumped. Compared to other pressurized systems, savings are also made because of the lower operational water pressure required for drip systems.	**Operation, maintenance and lifespan:** Though drip irrigation has relatively simple O&M procedures, the durability is affected by their fragility and proneness to puncturing by sharp objects especially during weeding. They are also prone to damage by rodents like rats, squirrels and moles. Thus, lifespan is subject to good management and control of rodents.
Reduced salinity hazards: When the drip lines are placed close to a row of plants, the root zone tends to be relatively free of salt accumulations as the salts always accumulate towards the edge of the wetted area. Since the drip irrigation system can supply water frequently, the irrigation regime has a zone of wetted soil with a lowered salt content, which is beneficial for root activity.	**Salt accumulation in the root zone:** Unlike surface and sprinkler irrigation systems, which can flush out salts below the crop root zone, surface drip irrigation systems tend to move salts to the outer edge of the wetted volume of soil and soil surface. Careful management is therefore necessary to ensure that the salts do not migrate back to the active root zone.

Table 44: Key factors relevant for the implementation of small-scale drip irrigation systems.
Source: adapted from Staufer (2010).

System	Description	Advantages	Disadvantages	Costs	Suitability
Low-cost drip irrigation	Water flows through a filter into special drip pipes. Water is distributed through the emitters directly into the soil near the roots.	High effectivity. Water conservation. Reduction of evaporation. Reduction of deep drainage. High performance. Small-scale drip systems can be operated by trained farmers.	Maintenance requirements	Simple self-made systems are cheap (USD 20). Built with locally available materials (buckets, bamboo, plastic pipes, etc.).	Arid and semi-arid areas: Higher suitability for small-scale farming at community-based level.

10.4.3 Manual irrigation

The most common small-scale irrigation method in sub-Saharan Africa in general, and Ethiopia, Kenya, Mozambique and Zimbabwe in particular, is manual irrigation by means of the use of a watering cans, buckets or jerry cans (Fraiture and Giordano, 2014; De Trincheria et al., 2016) (Figure 64). Water can also be applied through a spout fitted with a shower rose. Manual irrigation systems are technically simple and easy-to-handle effective irrigation methods for making water available to crops (Stauffer and Spuhler, 2010a). In addition, the systems

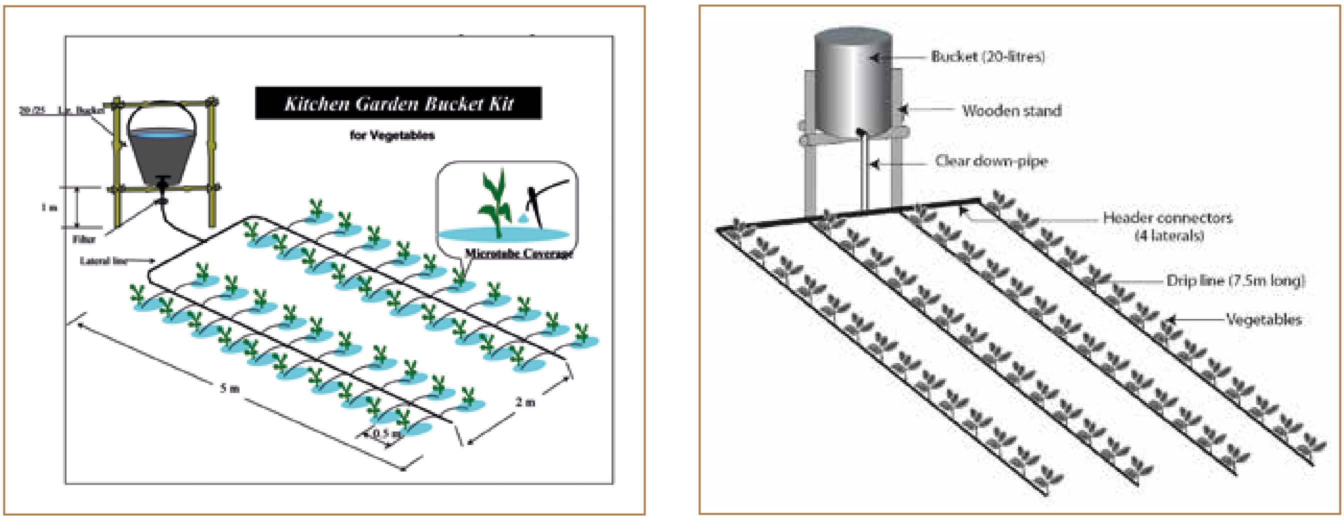


Figure 61: 20-litre bucket kit LHLCD irrigation system (Ngigi, 2009).

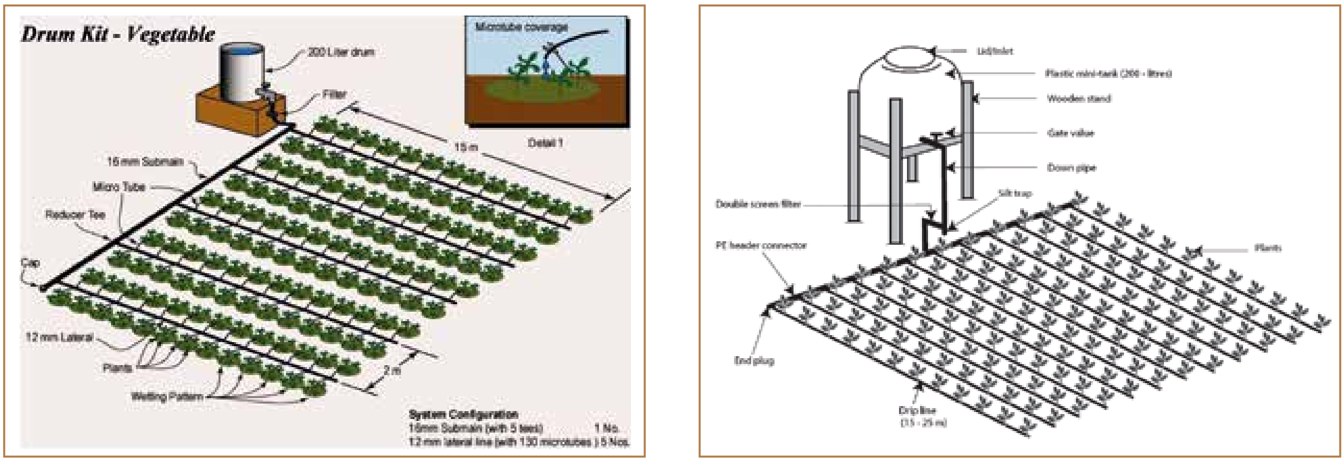


Figure 62: A typical 200-litre mini-tank (drum) LHLCD irrigation system (Ngigi, 2009).

Figure 63: A LHLCD irrigation system for horticulture production in Ethiopia (left) and Kenya (right).
Photos: S. Ngigi.

allow for high self-help compatibility, have low initial capital costs and are suitable for almost every area, especially arid and semi-arid areas (Stauffer and Spuhler, 2010a). This type of irrigation methods are also called HELPFUL irrigation methods: High-frequency, Efficient, Low-volume, Partial-area, Farm-Unit, and Low-cost (FAO 1997).

However, if not controlled, manual irrigation can lead to over-irrigation, leaching of nutrients and poor water management. In addition, they are labour-intensive and need to be constructed correctly in order to avoid water loss and crop shortfall (Stauffer and Spuhler, 2010a). Table 45 shows key factors relevant for the implementation of small-scale manual irrigation systems.

The application of manual irrigation systems is usually limited to kitchen gardening or small-scale vegetable production along the riverbanks of streams and/or nearby surface water reservoirs. Traditionally, a bucket is used for hand-watering, but where gravity or pumped water supply is available, a garden hose or a portable sprinkler can also be used. Hand watering with a hose is common, but it is difficult to apply water evenly and consistently to mature plantings. Manual irrigation is especially suitable for watering seeds.

A very water-efficient type of manual irrigation system revolves around implementing small-scale drip irrigation using porous clay jars, bottles or pipes (Stauffer and Spuhler, 2010a) (Figure 65). These systems are low-cost, easy to install and simple to use (Stauffer and Spuhler, 2010a). Table 46 shows an overview of these technologies and Table 47 specific advantages and disadvantages of these systems.

Figure 64: Manual irrigation of horticultural crops.
Photos: J. de Trincheria.

10.4.4 Low-tech automatic irrigation systems

According to Stauffer and Spuhler (2010c), a low-tech automatic irrigation system refers to the operation of a simple irrigation system with no or just a minimum of manual intervention beside the surveillance. These authors also state that it makes the irrigation process more efficient and farmers can concentrate on other farming tasks. However, such a system can be complex in its design and requires high levels of technical expertise (Stauffer and Spuhler, 2010c).

Table 45: Key factors relevant for the implementation of small-scale manual irrigation systems.
Source: adapted from Staufer and Spuhler (2010a).

System	Description	Advantages	Disadvantages	Costs	Suitability
Manual irrigation	Water is delivered to the cropping area manually.	Simple. Effective. No need of technical equipment. Reduction of evaporation.	High labour and time requirements.	Low initial capital costs.	Arid and semi-arid areas: High suitability for small-scale farming at household level or riparian communities.

Table 46: Manual drip irrigation systems.
Source: Adapted from Stauffer and Spuhler (2010a).

System	Description
Pitcher irrigation	Consists in placing porous clay jars in shallow pits dug for this purpose. Soil is then packed around the necks of the jars so that their rims protrude a few cm above the ground surface. Water is poured into the jars either by hand or by means of a flexible hose connected to a water source. Since the walls of the pots are porous (i.e. unglazed pots), the water can seep slowly out and reach the roots of the plants.
Bottle Irrigation	Pitcher irrigation can also be done using a bottle. The bottle is first filled and then placed with its neck into the soil next to a plant, so it stands upside down. The dense soil hinders the water from leaving the bottle immediately. Instead, it gets released slowly and directly besides the roots, so it is available to the plant for a longer time and the water cannot evaporate directly.
Porous and Sectioned Pipes	Another variation of pitcher irrigation uses porous pipes to spread water along a continuous horizontal band in the soil, rather than at discrete locations. As such, the porous pipe method is more suitable for closely spaced row crops grown in beds, such as vegetable crops. One end of the porous pipe is made protrude above ground in order that the operator is able to refill it with water as soon as it is necessary.

Table 47: A detailed overview of advantages and disadvantages of manual drip irrigation systems.
Source: Adapted from Stauffer and Spuhler (2010a).

Advantages	Disadvantages
Improved water-use efficiency (reduced loss through evaporation). Well directed, selective and targeted irrigation. Ensures constant water supply in the crucial phase of germination. Higher yields, better quality, higher germination rate, lower incidence of pest attack. Facilitates pre-monsoon sowing. Can be constructed with locally available materials. Low investment costs.	Labour intensive. User needs a basic training to install and use the correct the method. If the water is not properly filtered and the equipment not properly maintained, it can result in clogging. Manual subsurface drip irrigation avoids the high capillary potential of traditional surface applied irrigation, which can draw salt deposits up from deposits below.

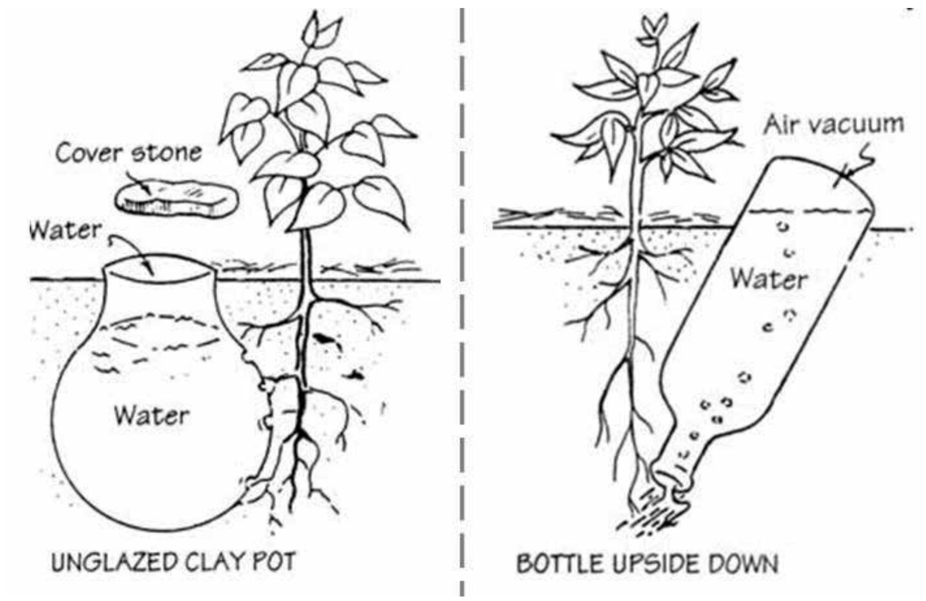


Figure 65: A low-cost manual drip irrigation system using clay pots (left) and bottles (right).
Source: (Staufer and Spuhler, 2010a from INFONET-BIOVSION, 2010).

Table 48 shows key advantages and disadvantages of this type of irrigation systems.

The main types of low-cost automated irrigation systems highlighted in these training materials are show in Table 49 and Figure 66.

10.4.5 Surface irrigation

Most smallholder irrigation schemes in sub-Saharan Africa usually apply surface irrigation (De Fraiture and Giordano, 2014). These methods involve the diversion of water from dams by gravity or mechanised pumping. The water is then conveyed by means of mainly open channels or pipes to the cropped area. Canals, which are lined

Table 48: Key advantages and disadvantages of low-tech automatic irrigation systems.
Source: Adapted from Stauffer and Spuhler (2010c).

Advantages	Disadvantages
No or just a minimum of manual intervention beside the surveillance. Farmer can focus on other tasks. Increased efficiency in water and fertiliser use. System can be operated at night, water loss from evaporation is thus minimised.	High technical complexity. Requires technical expertise to design the system.

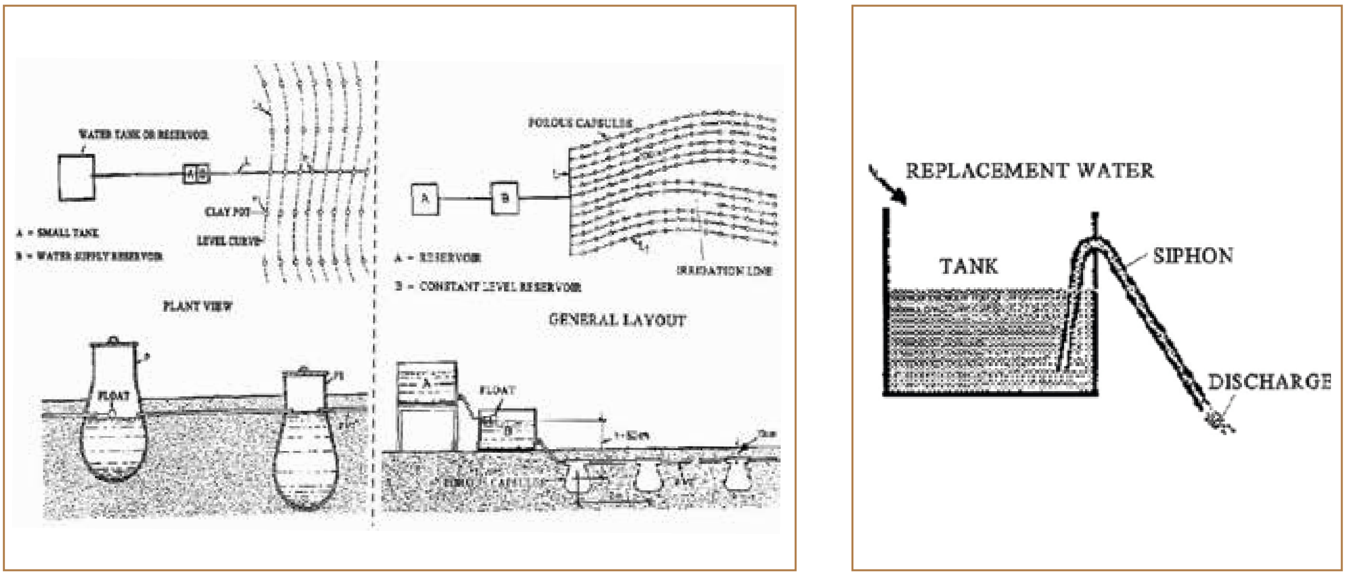


Figure 66: A clay pot and porous capsule irrigation network (left) and a syphon (right). Source: (Stauffer and Spuhler, 2010c from UNEP, 1998).

Table 49: Low-cost automated irrigation systems.
Source: Adapted from Stauffer and Spuhler (2010c).

System	Description
Clay Pot and Porous Capsule Irrigation Network	This irrigation systems is based on the manual pitcher irrigation system. It is based on storing and distributing water to the soil, using clay pots and porous capsules interconnected by plastic piping. A constant-level reservoir is used to maintain a steady hydrostatic pressure.
Automatic Surge Flow	This is an intermittent gravity-flow irrigation system. It has been used almost exclusively for small-scale agriculture and domestic gardening. The system consists of a storage tank equipped with one or more siphons. The water in the tank flows to the field because of the siphon effect. As soon as the tank is empty, the flow stops.
Gravitational Tank Irrigation System	A storage tank with a bottom discharge can also be used as a low-cost automated irrigation system. It is equipped with a floater, which allows the cyclical opening and closing of a gate at the bottom of the tank. The materials normally used in the construction of the water storage tanks are gravel and cement, reinforced concrete or plastic.

or unlined, are also used to direct water into the fields. Unlined canals are popular among the resource-poor farmers because of low initial costs. Water can also be conveyed to the fields by using pipes fitted with or without sprinklers. However, the water distribution is uncontrolled and therefore, inherently inefficient. The major types of surface irrigation are basin, furrow and border strip. In addition, it is more labour intensive than other irrigation systems (Stauffer and Spuhler, 2010b). Table 50 shows a detailed overview of advantages and disadvantages of this type of irrigation systems.

10.4.6 Sprinkler irrigation

A sprinkler irrigation system distributes water through a system of pipes (usually by pumping or gravity) in order to spray it into the air through sprinklers in the form of water drops. Most of the sprinklers are either rotating or fixed head. Sprinkler irrigation is subject to water loss by wind drift, increased evaporation, or poor application uniformity, especially with strong winds (Ngigi, 2008b). In addition, sprinkler irrigation systems can either be classified as portable, semi-portable, semi-permanent or permanent on one hand, and set-move, solid-set, or continuous move on the other, depending on their installation and operating principles.

For RWHI systems, locally-available movable low-head sprinklers and micro-sprinklers (with movable laterals or hose pipe connecting to one or more sprinklers) are more appropriate. However, their applicability depends on the area under irrigation, water availability, and type of pumping system. Table 51 provides an overview of key factors relevant to the implementation of small-scale sprinkler irrigation systems.this irrigation systems.

Table 50: Advantages and disadvantages of surface irrigation systems.
Source: (Staufer and Spuhler, 2010b quoting Walker, 1989).

Advantages	Disadvantages
It is widely utilised so local irrigators generally have at least minimal understanding of how to operate and maintain the system. Can be developed at the farm level with minimal capital investment. The essential structural elements are located at the edges of the fields, which facilitates operation and maintenance activities. If the topography is not too undulating, costs are not great. Energy requirements for surface irrigation systems come from gravity. Surface irrigation systems are less affected by climatic and water quality characteristics. The gravity flow system is a highly flexible, relatively easily managed method of irrigation.	The soil, which must be used to convey the water over the field, has properties that are highly varied both spatially and temporally. Surface irrigation systems are typically less efficient in applying water than either sprinkler or trickle systems. The need to use the field surface as a conveyance and distribution facility requires that fields be well graded if possible. Surface systems tend to be labour-intensive.

Table 51: Key factors relevant for the implementation of small-scale sprinkler irrigation systems.
Source: adapted from Staufer and Spuhler (2010d).

System	Description	Advantages	Disadvantages	Costs	Suitability
Sprinkler irrigation	Rainfall-like irrigation to the crops through a system of pipes usually by pumping.	Suitable for all types of crops and irrigable soils.	Clogging. High evaporation losses. Sensitivity to crop diseases.	Low capital investment for small sprinkler equipment for gardening. High operation costs due to expenses for pumping, labour and sprinklers and pipes.	Low suitability to arid and semi-arid areas and resource poor farmers with the exception of movable low-head sprinklers and micro-sprinklers.

10.4.7 Greenhouses for weather-sensitive crops

To grow high-value crops under controlled conditions ensures quick returns to the investment because under optimal growing conditions, vegetables and fruits can produce up to ten times more than rainfed conditions (Ngigi, 2009). However, most smallholder farmers cannot afford the high investment costs of greenhouses. To address this challenge, farmers are either opting for simple locally-constructed structures or taking credit from local banks/micro-finance institutions in order to acquire high-tech greenhouses (Figure 67).

Greenhouses are compatible with RWHI systems. Thus, their incorporation as complementary technology add value to the investments through assured and increased horticultural production (Ngigi and Oremo, 2015). The greenhouses have greatly intensified crop and water productivity: In 1 season, a smallholder farmer can recover the total investment costs for an on-farm pond system (USD 1,000) coupled with a 120 m^2 greenhouse (USD 1,200) because the total seasonal revenue that can be generated is USD 2,000 - 2,500 (Ngigi et al., 2012). Without a greenhouse, seasonal return ranges from USD 250-600 depending on type of crops.

In sub-Saharan Africa, there are a number of private companies that are promoting various designs of greenhouses ranging from 6 m x 12 m to 8 m x 60 m. In addition, there are private companies marketing different components of the greenhouse technology such as plastic sheets and shade nets. However, construction works for the greenhouses require experienced and a technically-qualified person to ensure quality control. Further, most smallholder greenhouses incorporate a low-head drip irrigation system.

Enhancing RWHI management
A variety of innovative complementary technologies and practices can be coupled with off-season small-scale irrigation systems in order to improve their performance, efficiency and positive effects. Table 52 shows a summary of these systems.

Figure 67: Locally made wooden and metallic greenhouses for horticulture production.
Photos: S. Ngigi.

Table 52: Innovative complementary technologies to enhance off-season small-scale irrigation.

Technology	Description	Yields	Water saving	Reduced inputs	Product quality	Security	Employment
Low-cost water storage ponds by animal-driven excavation	Animal-driven dozers can accelerate the development of storage ponds in a variety of settings: The most appropriate is the Fresno scraper that has a tipping bucket and gliders.	x	x			x	x
Water storage with sealing agents	Sealing agents have been developed to make impervious and weather-proof low volume roads. The same technology can be used as a sealing agent for water ponds. This is an alternative for clay or geotextile.	x	x			x	
Hydroponics in greenhouses	Affordable greenhouses and hydroponics with specialist nutrient supply. The greenhouses have self-regulating temperature control and safe up to 80 % of power and water, whereas the nutritious value of the grown products is up to 140 % of the commonly grown crops.	x	x		x		
Biodegradable plastic mulch	Plastic films can come in different colours (transparent, black, white) to control soil moisture evaporation, soil temperature and suppress weed growth.	x					
Reel farming	Strips with nutrients and plant seeds to be introduced for school farming and homestead farming.	x	x				
Compost	Different types of compost to improve soil structure, water holding capacity and increase nutrient availability.	x	x	x			
Vermicomposting	With the use of earth worms, organic waste materials can be converted in high quality compost that improve fertility and moisture holding capacity.	x	x	x			
Sanitation link	Reuse of human manure and struvite in agriculture.			x			
Bokashi	Biofertilizer with good water holding capacities can add micronutrients.	x		x	x		x
Rock dust biofertilizer	Biofertilzier mixed with rock dust or zeolite increases the supply of micronutrients and fertiliser, and (though modestly) moisture holding capacity.			x	x		x
Tal-ya dew plates	Plates made of a special plastic that concentrates runoff and causes dew formation (in altitude areas) and suppresses the growth of weeds.	x	x				
Water pads	Combination of water absorbing polymers with layers of jute and paper: Creating a localized water buffer for plants, increasing chance of survival of young trees and plants.	x	x			x	
Groasis waterboxx	Water storage and dew collection device especially in water-stressed areas.					x	
Buried diffuser	Pressure system to be connected to a drip system in order to bring water into the root zone.		x	x			
Subsurface irrigation	Root zone irrigation though buried drip lines.	x	x			x	
Lay flat hoses	Polyethylene hoses connected to groundwater systems to reduce conveyance losses and increase extra head.		x			x	
Mulchers and harrowers	Different techniques to improve water absorption capacity of soil, regulating soil temperature and soil evaporation.	x	x			x	

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