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Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – A review

Birhanu Biazin [a,b,*], Geert Sterk [c], Melesse Temesgen [d], Abdu Abdulkedir [a], Leo Stroosnijder [b]

[a] *Hawassa University, Wondo Genet College of Forestry and Natural Resources, P.O. Box 128, Shashemene, Ethiopia*
[b] *Wageningen University, Land Degradation and Development Group, P.O. Box 47, 6700 AA Wageningen, The Netherlands*
[c] *Utrecht University, Department of Physical Geography, P.O. Box 80115, 3508 TC Utrecht, The Netherlands*
[d] *Addis Ababa University, Department of Civil Engineering, P.O. Box 385, Addis Ababa, Ethiopia*

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ABSTRACT

Agricultural water scarcity in the predominantly rainfed agricultural system of sub-Saharan Africa (SSA) is more related to the variability of rainfall and excessive non-productive losses, than the total annual precipitation in the growing season. Less than 15% of the terrestrial precipitation takes the form of productive 'green' transpiration. Hence, rainwater harvesting and management (RWHM) technologies hold a significant potential for improving rainwater-use efficiency and sustaining rainfed agriculture in the region. This paper outlines the various RWHM techniques being practiced in SSA, and reviews recent research results on the performance of selected practices. So far, micro-catchment and *in situ* rainwater harvesting techniques are more common than rainwater irrigation techniques from macro-catchment systems. Depending on rainfall patterns and local soil characteristics, appropriate application of *in situ* and micro-catchment techniques could improve the soil water content of the rooting zone by up to 30%. Up to sixfold crop yields have been obtained through combinations of rainwater harvesting and fertiliser use, as compared to traditional practices. Supplemental irrigation of rainfed agriculture through rainwater harvesting not only reduces the risk of total crop failure due to dry spells, but also substantially improves water and crop productivity. Depending on the type of crop and the seasonal rainfall pattern, the application of RWHM techniques makes net profits more possible, compared to the meagre profit or net loss of existing systems. Implementation of rainwater harvesting may allow cereal-based smallholder farmers to shift to diversified crops, hence improving household food security, dietary status, and economic return. The much needed green revolution and adaptations to climate change in SSA should blend rainwater harvesting ideals with agronomic principles. More efforts are needed to improve the indigenous practices, and to disseminate best practices on a wider scale.

1. Introduction

Subsistence rainfed agriculture is the mainstay of most African economies, and contributes 10–70% to their GDP. African agriculture, however, has the lowest rate of productivity increase in the world. Africa was the only major region with a decline in food production *per capita* in the years 1980–2000 (Sachs et al., 2004). In sub-Saharan Africa (SSA), 95% of the cultivated land is under rainfed agriculture, and an estimated 41% of the region's population (*ca.* 260 million) lives in drought-prone dry lands (Svendsen et al., 2009; UNCCD, 2009). SSA has less than 2% of the world's total irrigated land (Field, 1990). Apart from the physical water scarcity, irrigation is unaffordable in SSA, as direct investment costs alone can reach US$ 8300 ha^{-1} (FAO, 1992), and increase to US$ 18,000 ha^{-1} when indirect infrastructural costs are included (Rosegrant, 1997). Hence, for the near future, rainfed agriculture will be the dominant source of food for the region's burgeoning population.

However, water supplies in Africa are shrinking and highly variable. Concurrent with a huge population increase during 1970–1994, a 180% reduction in human water supply took place in Africa while the reduction in Europe was 16% (Shiklomanov, 2000). Year-to-year variability of renewable water resources is also high in arid and semi-arid regions where actual availability is limited. It has been estimated that in dryland regions, there could be 150–200% less renewable water resources in individual years than the long-term average, whereas in wet regions this difference is in the range of just 15–25% (Shiklomanov, 1998).

In addition to the scarcity and unreliability of annual rainfall, the loss of rainwater through non-productive pathways also seriously limits rainfed agriculture in SSA. Soil evaporation may reach

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[*] Corresponding author at: Hawassa University, Wondo Genet College of Forestry and Natural Resources, P.O. Box 128, Shashemene, Ethiopia. Tel.: +251 461109900; fax: +251 461109983.
E-mail address: Birhanutemesgen@yahoo.com (B. Biazin).

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50% of the rainfall (Daamen et al., 1995; Rockstrom et al., 1998; Stroosnijder and Hoogmoed, 1984). As much as 10–30% of the rainfall can be lost to surface runoff (Araya and Stroosnijder, 2010; Welderufael et al., 2008). Depending on the rainfall pattern, drainage can claim 10–30% of the rainfall (Klaij and Vachaud, 1992). Accordingly, more than 50% of the rainfall in dryland cropping systems may be lost non-productively. Stroosnijder (2009) argued that the fraction of rain used for plant transpiration can be as low as 15% of the terrestrial rainfall in SSA. In a worst case scenario, as in the Sahel region of Niger, only 4–9% of the rainfall takes the productive water-flow path as 'green' transpiration under a non-fertilised crop (Rockstrom et al., 1998).

Africa's dependence on rainfed agriculture means that it is susceptible to climatic variability which can severely affect food production and, therefore, human security and export revenues. Based on the assessment of vulnerabilities and risks of climate change in Kenya, Malawi and Ethiopia, climate-change emission scenarios revealed more extreme events in the future that could destabilise development activities (UNDP, 2007). River catchments are also sensitive to changes in regional climate which can be exacerbated by anthropogenic influences. For instance, with a 2 °C climate warming and a 10% reduction in precipitation, a 150–200% decrease in water resources is possible for regions located in the arid climate zones (Shiklomanov, 1998).

In eastern Africa, grain yields and growth in the overall agricultural gross domestic product depend heavily on the annual precipitation (UNDP, 2007). Farmers in semi-arid East Africa prioritise drought as their major productivity-reducing problem, while scientists identify soil degradation as a major threat (Slegers, 2008). In north-eastern Ethiopia, for example, drought-induced losses in crops and livestock between 1998 and 2000 were estimated at US$ 266 per household – greater than the annual average cash income for more than 75% of households in the region (Carter et al., 2004). In drylands, where water is even more limiting than land, improvement of agricultural water productivity ('more yield per drop') has been identified as a vital strategy. Satisfaction of the increased demand for food, water and material goods by a growing population, while at the same time protecting the ecological services of water, requires increased efforts towards doubling water productivity (Postel, 2000; Rockstrom, 2003).

Three-quarters of the additional food that the global population needs over the next several decades could be met by bringing the production level of the world's low-yield farmers up to 80% of that which high-yield farmers obtain from comparable lands (CAWMA, 2007). The greatest potential increases in yield are in rainfed areas, where many of the world's poorest rural people live, and where the management of water is the key to such increases (CAWMA, 2007). In SSA, there is no hydrological limitation to doubling the staple food production of the smallholder-based rainfed agriculture through better soil and water management techniques (Rockstrom et al., 2002). Rainwater harvesting is a growing technique to significantly increase water productivity, thus mitigating agricultural water scarcity and allowing increases in crop production levels. Multitudes of indigenous and recently developed rainwater harvesting techniques are used in different parts of SSA. Some of these indigenous techniques have been introduced and are being widely applied in the drylands of western Asia (Oweis et al., 2004). The techniques and modes of application, however, differ regionally. The best experiences in one country have the potential to be adapted in another country which has similar problems of water scarcity. To convince and attract more development partners and avoid scepticism about the significance of the technology in SSA, an overview of the contemporary research findings on the best experiences with rainwater harvesting is essential. Oweis and Hachum (2006) outlined the most important water-harvesting practices and their field performance for Western Asia and North Africa, but no such review exists for SSA. Therefore, the aim of this paper is to present a review of commonly applied RWHM practices in SSA, and report the current research findings concerning their biophysical and socioeconomic performance.

2. Scope and overview of rainwater harvesting and management techniques in SSA

In the past, the broad term 'water harvesting' has been used more frequently than 'rainwater harvesting' (Boers, 1994; Myers, 1975). Many authors have defined water harvesting and rainwater harvesting interchangeably, as 'the collection and storage of any form of water either from runoff or creek flow for irrigation use' (Boers and Ben-Asher, 1982; Critchley and Siegert, 1991; Falkenmark et al., 2001; Nasr, 1999; Oweis et al., 1999; Siegert, 1994). Although the ancient practices were primarily designed to meet domestic water needs, gradually the technologies also came to be used for agricultural purposes. In recent decades, scientists in SSA, the Middle East and Southeast Asia have made efforts to develop and test a wide variety of techniques for collecting, storing, and using natural precipitation for agricultural purposes (Humphreys and Bayot, 2009; Oweis et al., 2004; Rockstrom et al., 2002). Agricultural uses include the supplemental irrigation of crops, the provision of water for livestock, fodder and tree production and, less frequently, water supply for fish and duck ponds. Recently, the concept has been extended to encompass *in situ* techniques and appropriate land management practices which enhance infiltration and reduce surface runoff and soil evaporation (Rockstrom et al., 2002; Temesgen, 2007).

In the present paper, the more comprehensive and contemporary term 'rainwater harvesting and management' (RWHM) is used to encompass all practices of rainwater collection, storage and efficient utilisation for crop production (Ngigi et al., 2005; Rockstrom et al., 2002). RWHM practices being employed in SSA are discussed in four categories: (I) collection of surface runoff from micro-catchment systems with water storage in the soil for dry-spell mitigation, (II) collection of surface runoff from macro-catchment systems with water storage for supplementary irrigation, (III) techniques for maximising infiltration, reducing surface runoff and soil evaporation, and improving soil water availability, (IV) techniques for maximising plant water uptake and response farming.

2.1. Micro-catchment systems with water storage in the soil for dry spell mitigation

Micro-catchment rainwater harvesting systems are designed to collect runoff from a relatively small catchment area, mostly 10–500 m^2, within the farm boundary. The runoff water is usually guided into a type of infiltration enhancement structure and used to grow plants (Fig. 1). The ratio of the collection catchment to the cultivated target area can vary between 2:1 and 10:1 (Desta, 2007; FAO, 1991; Liniger et al., 2011). Unlike the macro-catchment systems, the catchment area can be easily controlled by the farmer which makes the systems easy to adapt and replicate.

The most commonly applied micro-catchment rainwater harvesting techniques in SSA include pitting, contouring, terracing and micro-basins (Table 1). Some of the techniques may have different names in different regions, and minor differences in design and use. *Zai* pits have been used in Burkina Faso for many years (Reij et al., 1996; Slingerland and Stork, 2000). Pits are dug 60 × 60 cm apart; and three to four grains of sorghum are planted in each pit (WOCAT, 2007). A similar type of pitting, the *ngoro* system, is used in steep (20–50%) sloping areas of Tanzania (Malley et al., 2004). In Niger, the traditional *tassa* system of cropping is employed by digging small planting holes of 20–30 cm diameter

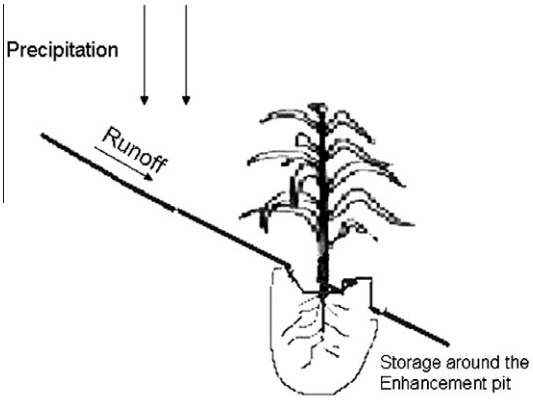

Fig. 1. Typical designation of the micro-catchment rainwater harvesting systems.

and 20–25 cm depth about 1 m apart in each direction, to hold pockets of rainwater and moisten the soil (Baidu-Forson, 1999; Kaboré and Reij, 2004). The combination of planting pits (*tassa*) with stone lines is used to rehabilitate degraded and crusted lands and bring them into cultivation (WOCAT, 2007). In response to sand encroachment on top of fertile soils, the planting of seedlings in shallow pits (5–15 cm deep and 10–30 cm wide) at intervals of 40–70 cm (*Magun cultivation*) has recently been adopted in semi-arid regions of Sudan (Osman-Elasha et al., 2006).

Micro-catchment water harvesting techniques that are being promoted throughout southern Zimbabwe include dead-level contours with or without infiltration pits, graded contour ridges (<5% slope) and *fanya juu terraces* (Kahinda et al., 2007; Mupangwa et al., 2006). In the field, the dead-level contours harness water originating from the area upslope. Planting pits (15 × 15 × 15 cm dimensions) are dug in September or October in the same positions annually, to collect rainwater in October and November before planting takes place in December (Mupangwa et al., 2006). Contour ridges vary in size, the smallest having cross-sectional dimensions of 1.5 m width and 0.5 m depth (Mupangwa et al., 2006). The basin and mulch technique is an innovative water-conservation technique used in South Africa to reduce total runoff to zero and soil evaporation considerably, thus improving crop yields (Bennie and Hensley, 2001; Botha et al., 2007). The *teras* system in Sudan, consisting of a field surrounded on three sides by low earth bunds, while the upstream side functions as an inlet for surface runoff, has been practiced for centuries (Niemeijer, 1998). Runoff harvesting on clay soils by constructing earth bunds (*trus* cultivation) was first used in 1964 and has also become common in the Darfur area of Sudan (Osman-Elasha et al., 2006). As rain-fed farming on sandy soils has become increasingly risky, indigenous *trus* cultivation has proved important in recent years. Soil and stone bunds, micro-basins, different types of terrace and trenches are some of the soil and water conservation practices in arid and semi-arid Ethiopia that are also used as micro-catchment rainwater harvesting systems (WOCAT, 2010). These techniques are commonly applied in areas characterised by low and erratic rainfall, and farming systems dominated by seasonal cereal crops such as maize (*Zea mays*), beans (*Vicia faba* L), pepper (*Capsicum annuum*) and tef (*Eragrostis tef*). The semi-circular terraces, which are mostly constructed at the foot of cultivated hill slopes, are used for moisture conservation in the drought-stricken Tigray region of Ethiopia (Annen, 2006). They have also recently been used to grow fodder plants and perennials such as fruit crops. Alley cropping and hedgerows have been used for soil and water conservation in eastern and western Africa (Kiepe, 1995a; Spaan, 2003).

In general, development of traditional practices has been more effective than introduction of new practices (Reij et al., 2009). A range of indigenous soil and water conservation practices has evolved in SSA (Critchley et al., 1994). In Kenya, *fanya juu* (Swahili for 'throw uphill') terraces have been developed and widely used to conserve soil and water (Kiome and Stocking, 1995). They are constructed by digging a trench and throwing soil up-slope to form an embankment. The broad bed and furrow system and chat ridge systems were developed in the degraded eastern drylands of Ethiopia (FAO, 2009). In the drought-affected and degraded lands of northern Ethiopia, stone bunds are constructed along the contour, 30 cm wide and average height of 0.74 m (Nyssen et al., 2007; WOCAT, 2010). They have been effectively used to reduce soil erosion, to shorten slope length and to retain soil moisture.

Table 1
Micro-catchment rainwater harvesting – Overview of the most commonly practised systems in sub-Saharan Africa.

Type of the micro-catchment systems	Description	Countries of wider application	References
Pitting (*Zai* pits, *Ngoro* pits, trenches, *tassa* pits, etc.)	*Zai* pits: A grid of planting pits is dug across plots that could be less permeable or rock-hard; organic matter is sometimes added to the bottom of the pits; *Ngoro* pits: A series of regular traditional pits, 1.5 m square by 0.1–0.5 m deep with the crops grown on the ridges around the pits; Trenches: pits are made along the contour sometimes with a bund downslope either staggered or continuous to check the velocity of runoff, conserve moisture and increase ground water recharge	West Africa (Burkina Faso, Mali, Niger) East Africa (Tanzania, Kenya, Somalia, Uganda, Ethiopia) Southern Africa (Zimbabwe, South Africa)	Malley et al. (2004), Mupangwa et al. (2006), Reij et al. (1996), WOCAT (2010)
Contouring (stone/soil bunds, hedge-rows, vegetation barriers)	Stone and soil bunds: A stone or sometimes earthen bank of 0.50–0.75 cm height is piled on a foundation along the contour in a cultivated hill-slope, sometimes stabilised with grasses or other fodder plant species; Hedge rows: Within individual cropland plots, strips of land are marked out on the contour and left unploughed in order to form permanent, cross-slope barriers of naturally established grasses and herbs. Alternatively, Shrubs are planted along the contour	East Africa (Kenya, Ethiopia, Tanzania) West Africa (Burkina Faso) South Africa	Kiepe (1995a), Spaan (2003), WOCAT (2010)
Terracing (*Fanya Juu*, Semi-circular and hillside terraces)	Bunds in association with a ditch, along the contour or on a gentle lateral gradient are constructed in different forms. The *Fanya Juu* terraces are different from many other terrace types in that the embankment is put in the upslope position	East Africa (Kenya, Ethiopia, Tanzania)	Tengberg et al. (1998), WOCAT (2010)
Micro-basins (Negarims, half-moons, and eye-brows)	Different shapes of small basins, surrounded by low earth bunds are formed to enable the runoff to infiltrate at the lowest point, where the plants are grown. The differences between the different structures is basically in their shapes, Negarims (diamond), Halfmoons (semi-circular), etc.	East Africa (Ethiopia, Kenya, Tanzania, Uganda) West Africa (Burkina Faso, Mali, Niger)	Abdulkadir and Schultz (2005), FAO (1991), Spaan (2003)

In southern Ethiopia, the farmers of Konso are well known for their own traditional terraces, the best locally available technique for soil and water conservation. About 80% of the cultivated land is well terraced in Konso (EPA, 2004). Vegetation barriers, using local grasses, woody species and succulents, can reduce soil erosion by 70–90% in an alley-cropping system in central Burkina Faso (Spaan et al., 2005). Hedgerows of *Cassia siamea*, grown in a maize/cowpea rotation on 14% slopes in the Machakos district of Kenya, enable an average increase in infiltration of 30% in the dry season and 94% in the wet season (Kiepe, 1995b). Different modifications have been made to some of these practices to improve their performance. For example, farmers in Burkina Faso adapted the *zai* pits by increasing their depth and applying compost and manure. Application of compost and manure in the pits conserves water and supplies nutrients, hence enabling sorghum plants to establish better, grow faster and reach maturity before the rains cease. Hence, improvement of water availability and fertility in the crusted desert soils restored productivity to the area (Reij et al., 2009; Spaan, 2003).

2.2. Macro-catchment systems with water storage for supplementary irrigation

The macro-catchment rainwater harvesting systems usually consist of three components: the rainwater collection catchment, the storage structure, and the target area (Fig. 2). In macro-catchment systems, the runoff is usually collected from external catchments and diverted into well designed storage structures. Although most of the macro-catchment rainwater harvesting techniques have a catchment area of less than 2 ha, in some cases runoff is being collected from catchments as large as 50 km^2 (Makurira et al., 2007). The water is used either for supplemental irrigation during dry-spell occurrences or for domestic consumption. The ratio of the collection catchment to the cultivated target area can vary between 10:1 and 1000:1 (Liniger et al., 2011). Rainwater is collected from existing paved surfaces and natural slopes, and rarely from purpose-built structures. Runoff collection from upslope rock outcrops was found to be effective in Botswana (Carter and Miller, 1991). The system components and the storage volume, catchment type and area, and water applications, depend on the local rainfall pattern and soil types (WOCAT, 2010).

The most commonly applied macro-catchment rainwater harvesting techniques in SSA encompass traditional open ponds, cisterns, micro-dams, sand dams and spate-irrigation systems (Table 2). Several of the widely applied macro-catchment rainwater harvesting techniques are indigenous or modified from indigenous practices. The *birkas* (runoff-fed underground tanks) in the eastern Somali region of Ethiopia, *ellas* (deep wells) in the southern Borena area of Ethiopia and *hafir* (low earth dams) in eastern Ethiopia, have been traditionally used for livestock and domestic water supply (Habtamu, 1999). In the Hiraan region of Somalia, the *caag* system is used where considerable overland flow, or flow from a small *toog* (gully), is captured behind bunds (Reij et al., 1996). However, the commonly used traditional open rainwater ponds do have a short lifespan after the rainy seasons, as the water is lost *via* seepage (except for rock catchment dams) and evaporation. Seepage is a major problem in water storage in earthen reservoirs, accounting for losses up to 69% of the harvested water (Fox and Rockstrom, 2003).

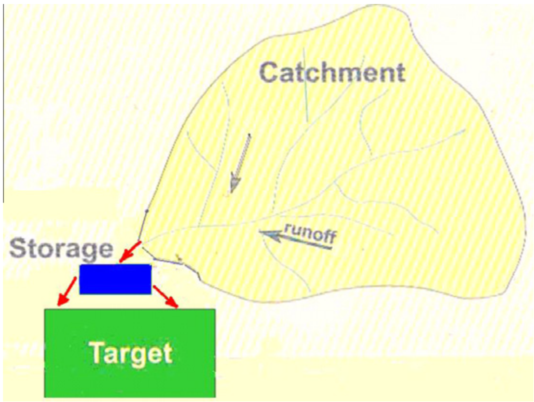

Fig. 2. A typical designation of the macro-catchment rainwater harvesting systems (modified from Oweis et al. (2001)).

Unlike the traditional open ponds, the recently developed cisterns in different parts of SSA are covered to reduce evaporation losses, and their walls are plastered to avoid seepage losses. The most important materials for construction and covering of these types of rainwater storage tank include cement, clay, clay–cement, lime–clay or lime–cement and polythene sheets. The cost of these materials makes macro-catchment rainwater harvesting systems expensive and poor farmers are discouraged from investing in them (Ngigi et al., 2005). However, in Ethiopia, locally available materials, such as termite-mound earth (either in blocks or as mud) are used to construct cisterns (Mills, 2004). Inspired by successful Chinese experiences, the Ethiopian government has given much attention to developing and promoting different designs of underground rainwater storage tanks—cisterns—in moisture-stressed, rainfed agro-ecosystems. Hence, in the four main administrative regions of Amhara, Oromia, Southern Region and Tigray, more than 340,000 cisterns were constructed in the years 2003–2004, mainly through government initiatives (Bekele et al., 2006).

Within the Kitui district of Kenya, about 500 sand dams have been developed over 10 years to store water for the dry season (Aerts et al., 2007). These sand dams are used for domestic water supply and irrigation, also enhancing groundwater recharge (Hut et al., 2008). The percentage of storage by sand dams relative to total seasonal runoff amounts to 3.8% for the April–October season and 1.8% for the November–March season (Aerts et al., 2007). In Tanzania, dugout ponds, which are found on roadsides where contractors have excavated soil for road construction, collect water, and villagers exploit this for domestic, livestock and vegetable production (Hatibu and Mahoo, 1999). In South Africa, *jojo* tanks of 0.75–20 m^3 have been popularised for collecting rainwater from rooftops, when it is used mainly for domestic purposes (Mokgope and Butterworth, 2001). Similar tanks of various designs have been promoted by non-governmental organisations in many African countries (Gould and Nissen-Petersen, 1999).

Spate irrigation is an indigenous technique of diverting and spreading seasonal heavy floods of short duration (Tesfai and Stroosnijder, 2001). It is commonly applied in SSA, in particular in Eritrea, Ethiopia, Kenya, Senegal, Somalia and Sudan. Farmers in Eritrea have used spate irrigation systems for more than 100 years, although modifications have recently been made through improved engineering skills (Tesfai and Stroosnijder, 2001). Similarly, a floodwater farming system known as *korbe* is practised in Ethiopia, which involves the diversion of water from various sources to grow vegetables, fruit trees and high-value crops on prepared land (WOCAT, 2010).

In addition to the simple diversion of storm flows from gullies and ephemeral streams into crop or pasture land, rainwater harvesting irrigation (RWI) from macro-catchment systems have eventually achieved recognition, as an alternative to conventional irrigation schemes (Rosegrant, 1997). There is a potential for reaching more than 30 million rural poor by applying supplemental irrigation to 15.2 million ha in SSA (Chartres, 2009). Supplemental irrigation, with about 100 mm of water provided during crucial dry spells, can double rainfed cereal yields from about 1 to

Table 2
Macro-catchment rainwater harvesting – Overview of the most commonly practised systems in sub-Saharan Africa.

Type of macro-catchment systems	Description	Storage capacity (m^3)	Countries of wider application	References
Traditional open ponds	Runoff collected from cultivated hill slopes, natural watercourses, footpaths or cattle tracks is stored in un-plastered and open ponds. The stored water usually suffers from losses due to seepage and evaporation	30–50	Mainly in East Africa (Kenya, Ethiopia, Tanzania, Somalia)	Habtamu (1999), Ngigi (2003), Reij et al. (1996)
Cisterns	Runoff collected from bare lands, cultivated hill slopes or road catchments is guided and stored in underground storage tanks. The cisterns have plastered walls and covered surfaces. In most cases, settling basins are attached in front of the inlet to reduce sedimentation and otherwise, regular cleaning is required	30–200	East Africa (Kenya, Ethiopia, Tanzania, Uganda) South Africa (Zimbabwe, Botswana)	Wondimkun and Tefera (2006)
Earthen dams (micro-dams)	Larger sized rainwater storage systems such as *ndivas* in Tanzania and micro-dams in Ethiopia are communally constructed around foots of hill slopes to store the runoff from ephemeral or perennial rivers. The reservoirs are neither plastered at their walls nor covered on their surfaces. The water is mostly used for supplemental irrigation communally and for cattle	$(0.02–0.2)10^4$ in Tanzania, and $(0.1–3.1)10^6$ in Ethiopia	East Africa (Tanzania, Ethiopia) Southern Africa (Botswana) West Africa (Burkina Faso)	Haregeweyn et al. (2006), Makurira et al. (2007)
Sand dams	Dams constructed to store part of the natural flow in seasonal rivers. The sand carried by the river will settle upstream of the dam and gradually fill the streambed. Hence, the sand will reduce evaporation and contamination of the water in the sand body behind the dam	–	East Africa (Kenya, Ethiopia)	Aerts et al. (2007), Hut et al. (2008)
Ephemeral stream diversions and spate irrigation	Ephemeral streams from uplands are diverted from their beds (*Wadis*) at the *agim* (temporary diversion structure) to irrigate adjacent crop fields downstream usually before planting	–	Mainly in East Africa (Eriteria, Ethiopia, Tanzania)	Hatibu and Mahoo (1999), Tesfai and Stroosnijder (2001), WOCAT (2010)

2 Mg ha^{-1}, increasing water productivity to 0.5 kg m^{-3} of water consumed (Araya and Stroosnijder, 2011; Rijsberman and Manning, 2006). Accordingly, the 50 m^3 rainwater tank commonly found in many parts of SSA could be used to apply supplemental irrigation for a farm plot of more than 500 m^2.

2.3. Techniques for maximising infiltration, reducing surface runoff and evaporation, and improving soil water availability

Techniques for enhancing infiltration, reducing runoff and evaporation or for improving soil moisture storage in the crop rooting zone, are known as *in situ* rainwater harvesting (Ngigi, 2003). These techniques generally do not need a runoff-inducing catchment area; rather, they are aimed at enhancing rainfall infiltration and reducing soil evaporation. The central idea behind these techniques is to turn blue water into green water to reduce direct soil evaporation, thereby causing it to be transpired through the plants (Falkenmark and Rockstrom, 2004). Better utilisation of rainfall to capitalise on green water requires appropriate land and crop management systems. Two distinct management periods are involved in maximising the use of precipitation for dryland crop production: the first period of rain storage, lasting from harvesting of the previous crop until planting of the next crop; and the second period, lasting from planting until harvesting of the crop (Bennie and Hensley, 2001).

The most commonly applied *in situ* rainwater harvesting and management practices in SSA include ridging, mulching, various types of furrowing and hoeing, and conservation tillage (Table 3). Ridging – also known as furrow dikes, furrow damming, basin listing, basin tillage and micro-basins in different areas (Jones and Stewart, 1990) – can be designed as open or closed (tied) for holding water and facilitating infiltration in areas of low, erratic rainfall. In tied-ridging, sometimes also called 'tied-furrows', ridge furrows are blocked with earth ties spaced at fixed distances to form a series of micro-catchment basins in the field (Nyamudeza and Jones, 1994; Wiyo et al., 1999). Surface mulching, using both crop residue and material such as stones from non-cultivated areas, has long been used in SSA (Tengberg et al., 1998; WOCAT, 2010). Stone mulching has been promoted in Burkina Faso to check soil erosion and conserve moisture (Zougmore et al., 2000). Conservation tillage (CT) in SSA encompasses a wide range of tillage techniques that have been tested and developed in many different places (Biamah et al., 1993; Fowler and Rockstrom, 2001; Temesgen, 2007). It covers a spectrum of non-inversion practices, from zero-tillage to reduced tillage, aiming at maximising infiltration and soil productivity, and minimising water losses while simultaneously conserving energy and labour. Recently, researchers have paid increasing attention to the development of appropriate conservation tillage practices suitable for dryland farming systems in SSA (ATNESA, 2010; Rockstrom et al., 2009).

Farmers in the northern drylands of Ethiopia make contour furrows at 2–4 m intervals – locally called *terwah* – for tef (*Eragrostis tef*) production (Gebregziabhere et al., 2009). These furrows trap water in the ridges in such a way that, after a storm, the fields will have elongated pools of retained water for later use by crops, instead of losing it as runoff. The traditional ridging and weed control practice known as *shilshalo*, is practised four weeks after planting of maize in Ethiopia (Birhane et al., 2006). In the central Rift Valley areas of Ethiopia, where sandy loam soils are sensitive to crusting, *shilshalo* is a means of breaking the surface crusts thereby enhancing infiltration (Biazin et al., 2011). The promotion of animal- and tractor-drawn conservation tillage among smallholder farmers in the semi-arid Babati district, Tanzania, using rippers and sub-soilers, has resulted in significant increases in water productivity in recent decades (Rockstrom et al., 2002). Similarly, in the semi-arid Laikipia district of Kenya small-scale conservation tillage, involving the use of ox-drawn rippers, was used to minimise soil disturbance and conserve soil moisture, while at the same time controlling costs and developing fodder (Liniger et al., 2011; WOCAT, 2007). In the semi-arid regions of the Sahel, where the soils are characterised by sealing, crusting, hard-setting and low organic-matter content, appropriate tillage techniques play a crucial part in improved infiltration and moisture conservation (Hoogmoed, 1999).

In Kenya farmers traditionally form *trash lines* from crop residues in surface strips along the contour, to mitigate erosion and exploit the trapped soil and moisture (Tengberg et al., 1998). This

Table 3
In situ rainwater harvesting – Overview of the most commonly practised and emerging systems in sub-Saharan Africa.

Type of structure	Description	Regions of current application	References
Ridging	Basins that are wider than the traditional furrows are created either by manual hoeing or during tillage using a modified ploughing instrument. They can be designed to be tied every 3–6 m distance for holding water and facilitating infiltration in low and erratic rainfall areas	Many parts of the SSA	Hulugalle (1990), Lal (1990), Wiyo et al. (1999)
Mulching	The use of both crop residues and material from non-cultivated areas, including stones, aimed at covering the soil. This improves infiltration of water into the soil and prevents evaporation out of the soil	Western and Eastern Africa	Tengberg et al. (1998), WOCAT (2010)
Furrowing and pot-hoeing	Different furrowing techniques are used before and after planting to conserve soil moisture in areas where oxen ploughing and hand-hoeing practices are common. In the Sahel, small shallow holes are dug manually at correct intervals and the seeds are covered with soil; Two weeks after the emergence of the crop they add fertiliser about 10 cm from the plant	Eastern and Western Africa	Birhane et al. (2006), Gebregziabhere et al. (2009), Nyssen et al. (2011)
Conservation tillage	It encompasses a wide range of tillage techniques ranging from non-inversion ploughing and reduced tillage to ripping and sub-soiling in SSA.	Many parts of SSA (South Africa, Kenya, Tanzania, Ethiopia)	Rockstrom et al. (2002, 2009), Temesgen (2007)

technique has also been promoted in the Kabale area of Uganda (WOCAT, 2007). In Uganda, dry vegetation is used to mulch bananas, pineapples and coffee in areas where soil moisture is a major constraint (WOCAT, 2010). Although appropriate application of crop residue mulch is essential to the rehabilitation of the desert soils in the Sahel (Mando and Stroosnijder, 1999), crop residues are often needed for income generation, or fed to livestock during the dry season, which limits the availability of mulch material in drylands (Sterk et al., 2001). *Loglines*, formed by logs unsuitable for charcoal production, are also used on recently cleared land as a soil and water conservation measure in Kenya (Okoba et al., 1998).

2.4. Techniques for improving plant water uptake and response farming

The experience of the past five decades has shown that genetic enhancements and appropriate agronomic management are important for increasing agricultural water productivity (Kassam et al., 2007). Genetic approaches to increasing the water productivity of crops encompass four traits (characters) of plants: (I) Traits that reduce the non-transpiration uses of water in agriculture, (II) Traits that reduce the transpiration of water without affecting productivity, (III) Traits that increase production without increasing transpiration and (IV) Traits that enhance tolerance of water stress (Bennet, 2003). As an example, early-maturing cultivars can escape droughts and provide yield even during years with below-average precipitation. A study conducted to determine the performance of late (120 days), early (90 days), and extra-early maturing (80 days) maize (*Zea mays* L.) cultivars, showed that extra-early maturing cultivars produced the highest dry matter yield, harvest index and grain yield in the Sudan Savannas of northeast Nigeria (Kamara et al., 2009). In another study, traits related to the ability of trees to extract and efficiently transport water, are suggested as the explanation for differences in drought resistance among species, and tree distribution in an arid savannah (Otieno et al., 2005).

Agronomic management for improved water productivity includes, but is not limited to, planting density and soil fertility management. Management of planting density according to the rainfall pattern has shown improved water and crop productivity in dryland rainfed systems (Tsubo and Walker, 2007). Too little plant density could lead to low utilisation of available soil water. The rapid establishment of a full ground cover due to a higher planting density can minimise the loss of water by evaporation from wet soil surfaces (Stewart and Steiner, 1990). The use of organic and inorganic fertilisers can also improve the water uptake capacity of crops. For example, farmyard manure improved the water-uptake capacity of grasses in the open grazing systems of Ethiopia (Taddesse et al., 2003). Managing optimum density that accord with a given crop requirements, different patterns of precipitation, and soil fertility can be valuable for improved water productivity.

Response farming is the system of predicting the seasonal rainfall at the start of each rainy season, and modifying the cropping systems accordingly (Stewart, 1988). The five key factors, which characterise a rainfall season for crop production, are: the onset and final rain dates, rainfall amount and distribution, duration, and intensity. The date of onset is of particular interest for two reasons (Stewart, 1988): (I) It occurs at the start of the season, before on-farm decisions are made, (II) It is highly variable and often a predictor of other rainfall attributes which occur later. On the basis of an analysis of long-term rainfall data, and knowing the crop response to different planting dates, it is possible to optimise the yield and water productivity of a given cropping system (Stewart, 1991). Analysis of long-term rainfall in the southern Sahelian and Sudanian zones revealed that delayed onset results in a considerably shorter growing season (Sivakumar, 1988). Hence, if the onset of the rains is delayed by 10 days beyond the calculated mean date of onset, short-duration cultivars or even alternative crops that will mature early, have a greater chance of being more productive (Sivakumar, 1988). Delaying the planting of maize generally increased days to flowering hence reduced dry-matter production and yield components (Kamara et al., 2009). Another study in Zimbabwe and South Africa showed that the late onset of rainfall during the maize growing season is associated with heavier rainfall, which could have negative consequences for crop yield if it leads to waterlogging (Tadross and Hewitson, 2005).

Apart from the onset, the distribution of rainfall throughout the growing season vitally affects crop productivity. For instance, agricultural dry-spell analyses from long-term rainfall data in two semi-arid regions of eastern Africa revealed that maize was exposed to at least one dry-spell of 10 days or longer in 70–84% of growing seasons (Barron et al., 2003). For many smallholder farmers in the semi-arid tropics, the risk of crop failure remains a reality every fifth year, with a risk of yield reductions every second year (Rockstrom et al., 2002). Farmers in semi-arid West Africa have tried to cope with low and erratic rainfall by, amongst other measures, decreasing planting density, replanting with early-maturing varieties or changing the crop type, and delaying fertiliser use (Matlon and Kristjanson, 1988). Recent advances in understanding and modelling of the oceanic atmospheric system at global and regional scales are important developments, which have enabled seasonal weather forecasting to assist farmers in optimising their immediate decisions and tactical planning with regard to the approaching season (Cooper et al., 2008). Response farming could be another potential research and development area for the future of green water capitalisation in SSA.

3. Research results on the performances of RWHM in SSA

3.1. Biophysical performances

Promising crop and water productivity performance has been observed from field evaluations of micro-catchment RWHM techniques in SSA. In the eastern drylands of Ethiopia, a field experiment was conducted to study the growth of four multipurpose tree species intercropped with grass (*Panicum maximum*) grown in plots with 25 m^2 and 100 m^2 micro-catchments (Abdulkadir and Schultz, 2005). The overall mean moisture content in the plots with micro-catchments was 31% higher in the wet season and 24% higher during the dry season, compared to that for plots without micro-catchments. The dry-matter content showed strong dependence on the area of the micro-catchments; the grass dry-matter yield was 32% greater on 100 m^2 plots, than on 25 m^2 plots. In Burkina Faso after the development of the *zai* pits, the farmers could rehabilitate their land and expand the size of their farms where nothing grew before (Kaboré and Reij, 2004). Thus, crop yield was 0 Mg ha^{-1} without them, 0.3–0.4 Mg ha^{-1} in a year of low rainfall, and up to 1.5 Mg ha^{-1} in a year of good rainfall. Similar studies on *ngoro* pits in Tanzania revealed that 2-m wide pits had the highest maize grain yield (1.85 Mg ha^{-1}) compared to 1-m wide (1.44 Mg ha^{-1}) and 1.5 m wide pits (1.66 Mg ha^{-1}) (Malley et al., 2004). A maximum level of soil moisture around the introduced trenches and bunds in semi-arid Tanzania confirmed their effectiveness in concentrating the little available rainfall into green water-flow paths (Makurira et al., 2009).

The use of macro-catchment systems for rainwater irrigation has shown positive crop and water productivity responses in semi-arid areas of SSA as well. A survey and modelling study in semi-arid Zimbabwe implied that RWI from macro-catchment systems increases water productivity, from 1.75 kg m^{-3} up to 2.3 kg m^{-3}, by mitigating intra-seasonal dry-spells (Kahinda et al., 2007). RWI from hand-dug earth dams, in combination with fertilisation, increased the rainwater use efficiency of maize from 2.1 kg m^{-3} (non-irrigated and without fertilisation) to 4.1 kg m^{-3} (supplemental irrigation and 30 kg N ha^{-1}) during seasons with poor rainfall (<300 mm) in Kenya (Barron and Okwatch, 2005). However, further studies are needed to bring about system improvements and to optimise RWI techniques. An on-farm study of rainwater harvesting irrigation by means of hand-dug earth dams in Burkina Faso showed that seepage losses accounted for 75%, and evaporation for about 5%, of the harvested dam water (Fox and Rockstrom, 2003). Similar studies in semi-arid Kenya revealed that seepage accounted for an average of 57%, and evaporation for an average of 12%, of the dam water (Barron and Okwatch, 2005). The irrigation efficiency of microdams (*ndivas*) in Tanzania was found to be very low; more than 80% of the water was lost during conveyance from the dams to individual fields (Makurira et al., 2007). Simple drip-irrigation kits have been widely regarded as the most promising technique, and have been successfully implemented in vegetable gardens in several countries of SSA (Karlberg et al., 2007). An on-farm study in a semi-arid area of Zimbabwe revealed that water savings of more than 50% were achieved in low-cost drip systems, compared to the conventional surface irrigation system (Maisiri et al., 2005). With this increase in water-use efficiency, a vegetable yield of 8.5 Mg ha^{-1} was obtained for drip irrigation, compared to 7.8 Mg ha^{-1} for surface irrigation. The overall irrigation efficiency of the traditional spate irrigation schemes in Eritrea is only about 20%, because of the difficulty of controlling floods and the loss of water *via* percolation, seepage and evaporation (Tesfai and Stroosnijder, 2001).

The crop and water productivity performance of *in situ* rainwater harvesting techniques has also been examined in a number of on-farm studies. A 3-year experiment conducted in the drought-stricken areas of Wollo region, Ethiopia, revealed that tied-ridging, open-ridging and sub-soiling improved soil water content in the root zone by 24%, 15% and 3%, respectively, as compared to traditional tillage during the cropping season (McHugh et al., 2007). In the semi-arid region of northern Ethiopia, where a significant proportion of the rainfall is lost as runoff, tied-ridges reduced surface runoff by about 60%, improving the soil–water content in the rooting zone by at least 13% (Araya and Stroosnijder, 2010). Accordingly, the grain yield of barley (*Hordeum vulgare*) could be improved by at least 44%. The moisture-retention capacity of tied-ridges was significantly higher than that of conventional tillage under sandy soils in Zimbabwe (Motsi et al., 2004). Thus the yield of maize under tied-ridges was twice that under conventional tillage without ridges. The tied-furrow system maintained significantly larger amounts of water in the soil, compared with flat cultivation, throughout the sorghum (*Sorghum bicolor* (L.) *Moench*) growing season in Zimbabwe (Nyamudeza and Jones, 1994). Earlier experiments in the West African Savannah also showed that runoff ranged from 0% to 15% with tied-ridging, whereas with either open ridging or flat planting, 20–40% of seasonal rainfall was lost as runoff (Hulugalle, 1990).

An on-farm experiment by Hensley et al. (2000) and simulation of crop yields with model combinations by Walker et al. (2005) in a clay soil of semi-arid South Africa showed that rainwater harvesting with basin tillage and mulching increased maize yields by 30–50%, depending on the initial soil water conditions. A field experiment conducted to examine the effect of stone mulching in Burkina Faso revealed that sorghum straw and grain yield were doubled on plots with stone lines, compared to that on plots without stone lines (Zougmore et al., 2000). The soil water content decreased with increasing distance from the stone lines. The use of improved tillage through adaptation of the existing traditional *maresha* ploughing practices in semi-arid Ethiopia increased the yield of tef (*Eragrostis tef*) by 13–19% as compared to traditional tillage (Temesgen, 2007). A study in South Africa also revealed that better maize yields were obtained from no-tillage farming as compared to conventional tillage (Kosgei et al., 2007). However, because the effect of no-tillage farming on improving soil water status and crop yields depends on climate and soil type, local tests are required before the method is more widely applied.

The combined application of rainwater harvesting and soil fertility improvements has shown promising performances. Some rainwater management techniques, such as the *teras* system in Sudan, contribute directly and significantly to soil fertility through the deposition of sediment and organic matter (Niemeijer, 1998). In other cases, it is the addition of compost, manure or processed fertiliser to a system where RWHM is being employed that provides the increased benefit. In a semi-arid area of Burkina Faso, where sorghum production without water conservation techniques is very difficult, combining compost or animal manure with half-moon structures allowed yields between 0.9 and 1.6 Mg ha^{-1} i.e. 20–39 times that obtained in the half-moon without any compost or manure (Zougmore et al., 2003a). A combination of manure application with *zai* pits in Burkina Faso also resulted in a more than twofold grain yield, compared with that obtained without manure (Fatondji et al., 2006). More than 5000 households have adopted composting in association with planting pits in the Boulgou province of Burkina Faso (WOCAT, 2007). In another on-farm study carried out in Burkina Faso, supplemental irrigation increased sorghum harvests by only 56%, but in combination with added fertiliser, by 208% (Fox and Rockstrom, 2003). As shown by a

3-year experiment in semi-arid Tanzania, tied-ridging in combination with inputs of mineral fertiliser could increase maize grain yield from 1 Mg ha^{-1} (under flat planting with no mineral fertilisers) to 6 Mg ha^{-1}, and hence, the rainfall productivity (grain yield per unit of annual rainfall) could be tripled in near-normal rainfall years (Jensen et al., 2003). In the mixed crop–livestock systems of SSA, Integrated Soil Fertility Management (ISFM), combining different methods of soil fertility amendment with soil and water conservation, is found to be suitable (Liniger et al., 2011). ISFM involves maximising the use of organic sources of fertiliser, minimising the loss of nutrients, and judicious use of inorganic fertiliser according to need and economic availability. Many of these studies indicated that fertiliser application could substantially improve crop yields only in the presence of ample soil moisture. This implies that RWI is essential for encouraging fertiliser use by farmers who may not otherwise be willing to apply it, owing to the risk of crop failure caused by dry spells and drought.

The effect of the various RWHM practices on water and crop productivity depends on the rainfall pattern (Stroosnijder, 2007, 2009). In rainfed lowland rice fields of south-eastern Tanzania, soil bunds can give a minimum yield increase of 30% in normal years, whereas in wet years and when the soil hardly drains (drainage class 0–5 mm day^{-1}), the yield may even double (Raes et al., 2007). Hatibu et al. (2006) indicated that investments in rainwater harvesting for paddy rice production in Tanzania give more benefits during above-average seasons compared to below-average ones. During years with well-distributed rainfall in the Sahel, water-conservation measures without addition of nutrients had little influence on crop yields (Zougmore et al., 2003b). Hence, in years with well-distributed rainfall, application of nutrients alone resulted in much higher grain yields than did water-conservation measures without nutrient inputs. Mugabe (2004) reported that the difference in soil water content between access tubes at different distances from the *zai* pits was higher during dry spells, when tubes situated closer to the pits showed better soil–water status. Despite the beneficial effect of tied-ridges in years of near-normal (500–600 mm) rainfall, in wet years (700–900 mm) waterlogging effects were observed on maize in Tanzania (Jensen et al., 2003). Hence, larger applications of fertiliser were recommended for alleviating excessive wetness by increasing water loss *via* transpiration. It is also imperative to consider the time of ridging, to obtain the best performance of the crop from it. Birhane et al. (2006) confirmed that tied-ridging before or at planting in arid areas of Tigray, Ethiopia resulted in a better soil–water status and the best crop performance, compared with tied-ridging after planting, especially when planting was in the furrow. Accordingly, pre-planting rain storage efficiencies could be improved by 2–37% by increasing the fallow period. On the other hand, Temesgen (2007) revealed that in the semi-arid Rift Valley of Ethiopia, the longer the interval between tied-ridging and sowing, the less were the water-conservation efficiency and the maize yield, provided that there was minimum rainfall in the interval.

3.2. Economic costs and benefits of RWHM

A number of studies have been undertaken to investigate the economic costs and benefits of rainwater harvesting and management in SSA. A detailed socioeconomic assessment was undertaken, with 1517 households in the four main administrative regions of Ethiopia, to examine the impact of micro-catchment and macro-catchment agricultural water-management techniques (Awulachew et al., 2008). The agricultural income (from both crops and livestock) was significantly ($p < 0.0001$) higher for users than for non-users of the techniques. An economic performance evaluation of rainwater harvesting techniques at field scale in Tanzania also indicated that investment in RWH for maize, paddy rice and onion productions was profitable in the long term, as long as farmers could afford the initial investment (Senkondo et al., 2004). Fox et al. (2005) made a cost-benefit analysis of rainwater harvesting for supplemental irrigation under maize (*Zea mays* L. var. Katumani B) in Kenya, and for sorghum (*Sorghum bi-color*, IRAT 204) in Burkina Faso, by setting the labour cost equivalent to the income forgone (income generated during an equivalent time spent in alternative production). Thus in Burkina Faso, from an earthen dam of volume 300 m^3, a net profit of US$ 151–626 ha^{-1} $year^{-1}$ was obtained, compared to a loss of US$ 83 to a meagre profit of just US$ 15 ha^{-1} $year^{-1}$ for current farming practices, depending on the labour opportunity cost. The net profit in Kenya was US$ 109–477 ha^{-1} $year^{-1}$ as compared to US$ 40–130 ha^{-1} $year^{-1}$ for current farming practices (Fox et al., 2005). The use of farm ponds for supplemental irrigation of maize, based on the two rainy seasons in Kenya, also provided net seasonal revenue of US$ 150, which could increase the annual return by 150% (Ngigi et al., 2005). This would give net revenue of US$ 300 *per annum*, based on the two yields from the two rainy seasons, and hence would require a payback period of four seasons. Rainwater harvesting linked to road catchments for production of paddy rice in Tanzania gave a gross margin of return of more than US$ 12 per person-day invested (Hatibu et al., 2006). These benefits are very high, because without rainwater harvesting, it is not possible to produce paddy in the study area, and a rainfed sorghum crop realises a return on labour of only US$ 3.7 per person-day during above-average seasons. However, the same study implied that investment to improve the rainwater harvesting systems by including storage ponds is not beneficial, owing to a higher labour requirement. Moreover, farmers in Ethiopia who have adopted rainwater harvesting irrigation properly have improved their dietary status (Desta, 2004).

The economic costs and benefits of the various RWHM techniques are highly influenced by nutrient inputs. Owing to the high cost of labour, transport and material inputs for the installation of stone rows or grass strips in Burkina Faso, these measures were not cost-effective without the addition of nutrients, although they gave a sorghum yield increase of 12–58%, particularly under poor rainfall conditions (Zougmore et al., 2004). In Burkina Faso, a field experiment was performed to assess the impact of organic and mineral sources of nutrients and combinations thereof in optimising crop production in tillage and no-tillage systems, and to assess the economic benefits of these options (Ouédraogo et al., 2007). Hence, organic or combined organic and mineral-derived nutrient applications were recommended, in combination with water-conservation techniques, for improved economic benefits under semi-arid conditions. A study in Tanzania implied that those farmers who adopted macro-catchment rainwater harvesting (*ndiva*) systems tended to have better land management techniques (nutrient management and soil conservation) than non-users (Enfors and Gordon, 2008). A similar study in Ethiopia also indicated that the users of agricultural water-management techniques used more farm inputs (fertiliser and better seeds) than non-users (Awulachew et al., 2008). Analysis of over 10 years of agro-hydrological and agro-economic studies in southern Africa implied that implementation of the Millennium Development food security goals can be achieved through the combined use of fertiliser, better seeds and agricultural water-management techniques (Love et al., 2006).

The types of crop grown substantially influence the economic benefits obtained from supplemental irrigation through rainwater harvesting as well. Short-term economic profitability of supplemental irrigation in SSA could be made possible by shifting the current cereal-based farming into high-value cropping systems (Chartres, 2009). For instance, the net income of supplemental irrigation was 76% higher for onion than for green maize, through supplemental irrigation in the semi-arid Ethiopian Rift Valley (Bekele et al., 2006). The crops cultivated through rainwater harvesting irrigation in the predominantly cereal-based northern regions of Ethiopia were mainly root crops and vegetables (Wondimkun and Tefera, 2006). Using macro-catchment rainwater harvesting systems, many farmers in semi-arid areas of Tanzania have changed from the cultivation of sorghum and millet to paddy rice on the seasonally flooded black-cotton soils (Hatibu et al., 2006). In Uganda, contour bunds in pasture fields increased the availability of fodder, hence the farmers could decide when and at what price to sell their livestock, rather than being forced to sell them at throwaway prices to avoid death due to frequent droughts (Ngigi, 2003).

For investments in rainwater harvesting to have an impact on poverty reduction, increased linkage to profitable markets is critical, as the results show that increased cash income is a leading priority of farmers (Hatibu et al., 2006). When a market is not available for vegetables produced through rainwater-harvesting investments, storage and transportation could be a risk. Investments in agricultural water, and other priorities, can contribute to poverty reduction and provide returns through several pathways, including: higher productivity; higher employment; higher income and consumption; better nutrition and health; better education; lower variability in output, income, and employment; improved equity; multiple uses of water; and multiplier effects on non-farm sectors (Hanjra et al., 2009).

Despite the promising socioeconomic potential of RWHM, meagre success has been achieved in the wider dissemination of externally introduced techniques in SSA. Complexity, establishment costs and lack of fit with local practices are some key reasons. In many countries, the types of technique and the way they are implemented vary, due more to the preference of the donors and projects than to any physical, socioeconomic and agronomic differences (Spaan, 2003). For instance, the introduced soil and water conservation technologies in the western highlands of Ethiopia were characterised by a majority of the sample farmers as highly labour-intensive, with difficult designs to construct, conflicting with the free-roaming livestock grazing system and inapt for the existing land-tenure system (Bewket, 2007). A study on the role of socioeconomic factors on the performance and effectiveness of dead-level contours in semi-arid Zimbabwe revealed that resource ownership was a key factor in affecting their performance and farmers' ability to scale out the techniques (Munamati and Nyagumbo, 2010). In Ethiopia, although properly designed and implemented cisterns showed promising performances, they could not easily be adopted by smallholder farmers, mainly due to their unaffordable establishment cost (Shiferaw, 2006).

4. Discussion and conclusion

Owing to physical and economic water scarcity, subsistence rainfed agriculture will continue to be the predominant source of food for the rapidly increasing population in SSA. The grave agricultural water scarcity in this region is more associated with the variability of rainfall and the large non-productive water flows, than with the total annual precipitation. In drought-prone SSA, less than 15% of terrestrial precipitation takes the form of productive green transpiration. Hence, rainwater harvesting and management techniques have a significant potential for improving and sustaining the rainfed agriculture in the region. A wide variety of micro-catchment, macro-catchment and *in situ* RWHM techniques is available in SSA. The indigenous techniques, or those modified from the indigenous RWHM practices, are more common and widely accepted by smallholder farmers than the introduced ones. A number of on-farm research results confirmed that micro-catchment and *in situ* RWHM techniques could improve the soil water content in the rooting zone by up to 30%, hence substantially reducing non-productive losses. However, in heavy rainfall seasons, some of the techniques, such as tied-ridging and stone lines, could cause waterlogging on maize and sorghum. Strategies to address this are needed. Although initial investments on macro-catchment rainwater harvesting systems may be beyond the capacity of the poor, long-term economic analyses confirmed the substantial net profits achievable, compared to meagre profits or even losses from existing smallholder-based farming systems. As long as dry spells during the growing season are a vital cause of crop failure or severe productivity decline in drylands, more has to be done to further promote adoption of RWHM techniques. This is especially needed in the case of supplemental irrigation through macro-catchment rainwater harvesting systems.

Genetic enhancements, response farming and appropriate agronomic management techniques are also vital to increasing agricultural water productivity. Based on the study of long-term rainfall characteristics and seasonal weather forecasts, it could be important to provide early-warning systems and to plan appropriate crop-management tactics in response to the rainfall pattern during the approaching season. Integration of rainwater harvesting with soil amendments has shown spectacular performances. Depending on the rainfall pattern and types of crop, twofold to sixfold increase in crop yields – sometimes far more – may be possible from combinations of RWHM and nutrient inputs, as compared to the traditional practices. Without rainwater management, for many smallholder farmers in the semi-arid tropics, it is simply not worth investing in fertilisation (and other external inputs) as long as the risk for crop failure remains a reality every fifth year with risk of yield reductions every second year, due to periodic water scarcity during the growing season (Rockstrom et al., 2002). In semi-arid western Africa, the use of N fertiliser alone was risky and a higher yield, with the accompanying economic benefit, was scarcely achieved under the prevailing rainfall conditions (Ouédraogo et al., 2007). The use of organic amendments, however, even without rainwater harvesting practices can contribute to increased water productivity and is affordable by the smallholder farmers. Continued research and development effort towards integrated RWHM, crop selection, and fertility management practices is needed in SSA.

Appropriate development of RWHM techniques is also irreplaceably vital as a practical and sustainable solution to the challenges of climate change and environmental degradation in this fragile region. Given the negative implications of climate change for the production of major agricultural crops in SSA (Schlenker and Lobell, 2010), rainwater harvesting will continue to be a viable adaptive strategy for people living with high rainfall variability, for countering droughts and mitigating flooding (UNEP, 2009). The Fourth Assessment Report of the International Panel for Climate Change (IPCC) has indicated that the expanded use of rainwater harvesting and other 'bottom-up' technologies, has the potential to reduce emissions by about 6 Gigatonne CO_2 equivalent $year^{-1}$ by 2030 (IPCC, 2007). Investigation of catchment hydrology in response to agricultural water use innovations indicated that rainwater harvesting through conservation tillage practices has influenced the partitioning of rainfall, by significantly reducing surface runoff over agricultural lands by up to 100%, as compared to conventional tillage (Kongo and Jewitt, 2006).

Three decades ago, rainwater harvesting and management technologies had limited attention by research and development actors (Tabor, 1995). Recently, there have been research and development efforts by a number of regional or international organizations working in SSA (Humphreys and Bayot, 2009; Liniger et al., 2011; Rockstrom et al., 2004; Twomlow et al., 2008). The efforts to incorporate remote sensing and modelling techniques for the assessment of agricultural water management techniques and catchment hydrological responses has shown encouraging achievements in the region (Bastiaanssen et al., 1998; Jewitt, 2006; Kongo et al., 2010; Kongo and Jewitt, 2006; Winnaar et al., 2007). However, the socioeconomic limitations to the development of appropriate RWHM technologies are still to be addressed. Farmers in SSA need technical and institutional support for developing their indigenous practices. The exemplary achievements of supplemental irrigation through rainwater harvesting for improved agriculture in the arid regions of China could be replicated in SSA, not only through appropriate support by local research and development, but also appropriate policy directives.

Facilitation of farmer-driven experimentation will allow farmers to methodically assess the value of the innovations they choose to study, while providing researchers with a venue for learning about socioeconomic as well as biophysical influences on farmers' decisions (Sturdy et al., 2008; WOCAT, 2007). There is a need to identify integrated rainwater harvesting systems and to utilise indigenous knowledge as a decision-support tool for appropriate development (Mbilinyi et al., 2005). A methodology flowchart has been proposed as a decision-support tool to systematically out-scale the impacts of the micro-catchment and macro-catchment rainwater harvesting techniques to a catchment scale (Ncube et al., 2008). Based on a review of the various indigenous soil and water conservation systems in SSA, Critchley et al. (1994) recommended that development projects need to incorporate indigenous practices in resource-conservation programmes. In northern Ethiopia, stone bunds could be popularised only after integrating them with the traditional knowledge of lynchets, locally called '*daget*' (Nyssen et al., 2000). Hence, more integrated efforts are needed to develop the indigenous practices, and to modify the introduced RWHM techniques in accordance with existing socioeconomic and biophysical settings. The much needed green revolution and adaptations to climate change in SSA should blend rainwater harvesting ideals with agronomic principles.

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References

Abdulkadir, A., Schultz, R.C., 2005. Water harvesting in a runoff-catchment agroforestry system in the drylands of Ethiopia. Agrofor. Syst. 63, 291–298.

Aerts, J., Lasage, R., Beets, W., de Moel, H., Mutiso, G., Mutiso, S., de Vries, A., 2007. Robustness of sand storage dams under climate change. Vadose Zone 6, 572–580.

Annen, T.C., 2006. From soil and water conservation to small-scale irrigation. Best practices and technologies for small-scale agricultural water management in Ethiopia. In: Proceedings of a MoARD/MoWR/USAID/IWMI Symposium and Exhibition Held, 7–9 March, Addis Ababa, Ethiopia.

Araya, A., Stroosnijder, L., 2010. Effects of tied-ridges and mulch on barley (*Hordeum vulgare*) rainwater use efficiency and production in Northern Ethiopia. Agric. Water Manage. 97, 841–847.

Araya, A., Stroosnijder, L., 2011. Assessing drought risk and irrigation need in northern Ethiopia. Agric. Forest Meteorol. 151, 425–436.

ATNESA, 2010. Animal Traction Network for Eastern and Southern Africa. <http://www.atnesa.org> (accessed 16.06.10).

Awulachew, A.B., Hagos, F., Loulseged, M., 2008. Agricultural water management and poverty in Ethiopia. In: Humphreys, E., Bayot, R.S. (Eds.), Proceedings of the Workshop on Increasing the Productivity and Sustainability of Rainfed Cropping Systems of Poor, Smallholder Farmers, Tamale, Ghana, 22–25 September, 2008, pp. 245–258.

Baidu-Forson, J., 1999. Factors influencing adoption of land-enhancing technology in the Sahel: lessons from a case study in Niger. Agric. Econom. 20, 231–239.

Barron, J., Okwatch, G., 2005. Run-off water harvesting for dry-spell mitigation in maize (*Zea mays* L.): results from on-farm research in semi-arid Kenya. Agric. Water Manage. 74, 1–21.

Barron, J., Rockström, J., Gichuki, F., Hatibu, N., 2003. Dry-spell analysis and maize yields for two semi-arid locations in east Africa. Agric. Forest Meteorol. 117, 23–37.

Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A., Holtslag, A.A.M., 1998. A remote sensing surface energy balance algorithm for land (SEBAL), Part 1: formulation. J. Hydrol. 212–213, 198–212.

Bekele, T., Kebede, H., Taddese, G., Peden, D., 2006. Small-scale irrigation practices and crop & livestock water requirements for better production by smallholder farmers: a cursory study on SG-2000 water harvesting and utilisation pilot project. Addis Ababa, Ethiopia.

Bennet, J., 2003. Opportunities for increasing water productivity of CGIAR crops through plant breeding and molecular biology. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. CABI Publishing, UK, pp. 106.

Bennie, A.T., Hensley, M., 2001. Maximising precipitation utilisation in dry land agriculture in South Africa. J. Hydrol. 241, 124–139.

Bewket, W., 2007. Soil and water conservation intervention with conventional technologies in north-western highlands of Ethiopia: acceptance and adoption by farmers. Land Use Policy 24, 404–416.

Biamah, E.K., Gichuki, F.N., Kaumbutho, P.G., 1993. Tillage methods and soil and water conservation in Eastern Africa. Soil Till. Res. 27, 105–123.

Biazin, B., Stroosnijder, L., Temesgen, M., Abdulkadir, A., Sterk, G., 2011. The effect of long-term *Maresha* ploughing on soil physical properties in the central Rift Valley of Ethiopia. Soil Till. Res. 111, 115–122.

Birhane, G., Wortmann, C., Mamo, M., Gebrekidan, H., Belay, A., 2006. Micro-basin tillage for grain sorghum production in semiarid areas of Northern Ethiopia. Agron. J. 98, 124–128.

Boers, Th.M., 1994. Rainwater Harvesting in Arid and Semiarid Zones – International Institute for Land Reclamation and Improvement. Publication No. 55. Wageningen, The Netherlands.

Boers, Th.M., Ben-Asher, J., 1982. A review of rainwater harvesting. Agric. Water Manage. 5, 145–158.

Botha, J.J., Anderson, J.J., Groenewald, D.C., Mdibe, N., Baiphethi, M.N., Nhlabatsi, N.N., Zere, T.B., 2007. On-farm application of in-field rainwater harvesting techniques on small plots in the central region of South Africa. Water Res. Commission, Report No. TT 313/07, pp. 1–9.

Carter, D.C., Miller, S., 1991. Three years experience with an on-farm macro-catchment water harvesting system in Botswana. Agric. Water Manage. 19, 191–203.

Carter, M.R., Little, P.D., Mogues, T., Negatu, W., 2004. Shock, sensitivity and resilience: tracking the economic impacts of environmental disaster on assets in Ethiopia and Honduras. Wisconsin, BASIS.

CAWMA, 2007. Water for food, Water for life: Comprehensive Assessment of Water Management in Agriculture. Earthscan, London.

Chartres, C., 2009. Funding the Blue Revolution: International Water Management Institute. IWMI. <http://www.iwmi.org> (accessed 12.12.09).

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? Agric. Ecosyst. Environ. 126, 24–35.

Critchley, W., Siegert, K., 1991. A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. FAO, Rome.

Critchley, W., Reij, C., Willcocks, T.J., 1994. Indigenous soil and water conservation: a review of the state of knowledge and prospects for building on traditions. Land Degrad. Rehab. 5, 293–314.

Daamen, C.C., Simmonds, L.P., Sivakumar, M.V.K., 1995. The impact of sparse millet crops on evaporation from soil in semi-arid Niger. Agric. Water Manage. 27, 225–242.

Desta, L., 2004. Rainwater harvesting and its role in food security – the Ethiopian experiences. In: Proceedings of the National Stakeholders' Workshop on Conservation Agriculture and Rainwater Harvesting in Ethiopia, November 17–19/2004, Addis Ababa, Ethiopia.

Desta, L., 2007. Regional training workshop on efficient water use for agriculture through water harvesting, June 4th–14th, Addis Ababa, Ethiopia.

Enfors, E., Gordon, L.J., 2008. Dealing with drought: the challenge of using water system technologies to break dry land poverty traps. Global Environ. Change 18, 607–616.

EPA, 2004. Environmental Protection Authority. The 3rd national report on the implementation of the UNCCD/NAP in Ethiopia, Addis Ababa, pp. 25–30.

Falkenmark, M., Rockstrom, J., 2004. Balancing Water for Humans and Nature: The New Approach in Ecohydrology. Earthscan, UK.

Falkenmark, M., Fox, P., Persson, G., Rockstrom, J., 2001. Water harvesting for upgrading of rainfed agriculture. Problem analysis and research needs. Stockholm International Water Institute, Report 11, Sweden.

FAO, 1991. A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. FAO, Rome.

FAO, 1992. Water for Sustainable Food Production-UNCED Agenda 21: Targets and Cost Estimates. FAO, Rome.

FAO, 2009. Water harvesting techniques. FAO corporate document repository. <http://www.fao.org/dooren/U3160E/U3160e07ht> (accessed 12.12.09).

Fatondji, D., Martius, C., Bielders, C., Vlek, P., Bationo, A., Gérard, B., 2006. Effect of planting technique and amendment type on pearl millet yield, nutrient uptake, and water use on degraded land in Niger. Nutr. Cycl. Agroecosyst. 76, 203–217.

Field, W.P., 1990. World irrigation. Irrig. Drainage Syst. 4 (2), 91–107.

Fowler, R., Rockstrom, J., 2001. Conservation tillage for sustainable agriculture: an agrarian revolution gathers momentum in Africa. Soil Till. Res. 61, 93–107.

Fox, P., Rockstrom, J., 2003. Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel. Agric. Water Manage. 61, 29–50.

Fox, P., Rockstrom, J., Barron, J., 2005. Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya. Agric. Syst. 83, 231–250.

Gebregziabhere, T., Nyssen, J., Govaerts, B., Getnet, G., Behailu, M., Haile, M., Dechers, J., 2009. Contour furrows for in-situ soil and water conservation, Tigray, Northern Ethiopia. Soil Till. Res. 103, 257–264.

Gould, J., Nissen-Petersen, E., 1999. Rainwater Catchment Systems for Domestic Supply: Design, Construction and Implementation. Intermediate Technology, London.

Habtamu, G., 1999. Rainwater harvesting concepts and issues. Paper presented at the founding conference of the Ethiopian Rainwater Harvesting Association (ERHA). December 17, 1999. Addis Ababa, Ethiopia.

Hanjra, M.A., Ferede, T., Gutta, D.G., 2009. Reducing poverty in sub-Saharan Africa through investments in water and other priorities: a review. Agric. Water Manage. 96, 1062–1070.

Haregeweyn, N., Poesen, J., Nyssen, J., de Wit, J., Haile, M., Govers, G., Deckers, S., 2006. Reservoirs in tigray (northern ethiopia): characteristics and sediment deposition problems. Land Degrad. Dev. 17, 211–230.

Hatibu, N., Mahoo, H., 1999. Rainwater harvesting technologies for agricultural production: a case for Dodoma, Tanzania. In: Kaumbutho, P.G., Simaleng, T.E. (Eds.), Conservation Tillage with Animal Traction: A Resource Book of the Animal Traction Network for Eastern and Southern Africa (ATNESA). Harare, Zimbabwe, 173p.

Hatibu, N., Mutabazi, K., Senkondo, E.M., Msangi, A.S.K., 2006. Economics of rainwater harvesting for crop enterprises in semi-arid areas of East Africa. Agric. Water Manage. 80, 74–86.

Hensley, M., Botha, J.J., Anderson, J.J., Van Staden, P.P., Du Toit, A., 2000. Optimising rainfall use efficiency for developing farmers with limited access to irrigation water. WRC Report No. 878/1/00. Water Research Commission, Pretoria, South Africa.

Hoogmoed, W.B., 1999. Tillage for soil and water conservation in the semi-arid tropics. Doctoral thesis. Wageningen Agricultural University, The Netherlands. ISBN: 90-5808-7026-9.

Hulugalle, N.R., 1990. Alleviation of soil constraints to crop growth in the upland Alfisols and associated soil groups of the Western African Savannah by tied-ridges. Soil Till. Res. 18, 231–247.

Humphreys, E., Bayot, R.S., 2009. Increasing the productivity and sustainability of rainfed cropping systems of poor smallholder farmers. In: Proceedings of the CGIAR Challenge Proram on Water and Food International Workshop on Rainfed Cropping Systems, Tamale, Ghana, 22–25 September, 2008, The CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka, 311 pp.

Hut, R., Ertsen, M., Joeman, N., Vergeer, N., Winsemius, H., de Giesen, N., 2008. Effects of sand storage dams on groundwater levels with examples from Kenya. Phys. Chem. Earth 33, 56–66.

IPCC, 2007. Summary for Policymakers: An Assessment of the Intergovernmental Panel for Climate Change, Valencia Spain, pp. 1–18.

Jensen, J.R., Bernhard, R.H., Hansen, S., McDonagh, J., Moberg, J.P., Nielsen, N.E., Nordbo, E., 2003. Productivity in maize based cropping systems under various soil–water–nutrient management in East Africa. Agric. Water Manage. 59, 217–237.

Jewitt, G., 2006. Integrating blue and green water flows for water resources management and planning. Phys. Chem. Earth 31, 753–762.

Jones, O.R., Stewart, B.A., 1990. Basin tillage. Soil Till. Res. 18, 249–265.

Kaboré, P.D., Reij, C., 2004. The emergence and spreading of an improved traditional soil and water conservation practice in Burkina Faso. Environment and Production Technology Division Discussion Paper 114. Washington, DC, IFPRI, pp. 1–28.

Kahinda, J.M., Rockstrom, J., Taigbenu, A.E., Dimes, J., 2007. Rainwater harvesting to enhance water productivity of rainfed agriculture in the semi-arid Zimbabwe. Phys. Chem. Earth 32, 1068–1073.

Kamara, A.Y., Ekeleme, F., Chikoye, K., Omoigui, L.O., 2009. Planting date and cultivar effects on grain yield in dryland corn production. Agron. J. 101 (1), 91–98.

Karlberg, L., Rockstrom, J., Annandale, J.G., Steyn, J.M., 2007. Low-cost drip irrigation – a suitable technology for southern Africa? An example with tomatoes using saline irrigation water. Agric. Water Manage. 89, 59–70.

Kassam, A.H., Molden, D., Fereres, E., Doorenbos, J., 2007. Water productivity: science and practice. Introduction. Irrig. Sci. 25, 185–188.

Kiepe, P., 1995a. No runoff, no soil loss: soil and water conservation in hedgerow barrier systems. Doctoral thesis. Wageningen Agricultural University, The Netherlands, pp. 156.

Kiepe, P., 1995b. Effect of Cassia siamea hedgerow barriers on soil physical properties. Geoderma 66, 113–120.

Kiome, R.M., Stocking, M., 1995. Rationality of farmer perception of soil erosion: the effectiveness of soil conservation in semi-arid Kenya. Global Environ. Change 5, 281–295.

Klaij, M.C., Vachaud, G., 1992. Seasonal water balance of a sandy soil in Niger cropped with pearl millet, based on profile moisture measurements. Agric. Water Manage. 21, 313–330.

Kongo, V.M., Jewitt, G.P.W., 2006. Preliminary investigation of catchment hydrology in response to agricultural water use innovations: a case study of the Potshini catchment – South Africa. Phys. Chem. Earth 31, 976–987.

Kongo, V.M., Jewitt, G.W.P., Lorentz, S.A., 2010. Evaporative water use of different land uses in the upper-Thukela river basin assessed from satellite imagery. Agric. Water Manage. doi:10.1016/j.agwat.2010.06.005.

Kosgei, J.R., Jewitt, G.P.W., Kongo, V.M., Lorentz, S.A., 2007. The influence of tillage on field scale water fluxes and maize yields in semi-arid environments: a case study of Potshini catchment, South Africa. Phys. Chem. Earth 32, 1117–1126.

Lal, R., 1990. Ridge-tillage. Soil Till. Res. 18, 107–111.

Liniger, H.P., Studer, R.M., Hauert, C., Gurtner, M., 2011. Sustainable Land Management in Practice – Guidelines and Best Practices for Sub-Saharan Africa. TerrAfrica, World Overview of Conservation Approaches and Technologies (WOCAT) and Food and Agriculture Organisation of the United Nations (FAO), pp 243.

Love, D., Twomlow, S., Mupangwa, W., van der Zaag, P., Gumbo, B., 2006. Implementing the Millennium development food security goals – challenges of the southern African context. Phys. Chem. Earth 31, 731–737.

Maisiri, N., Senzanje, A., Rockstrom, J., Twomlow, S.J., 2005. On farm evaluation of the effect of low cost drip irrigation on water and crop productivity compared to conventional surface irrigation system. Phys. Chem. Earth 30, 783–791.

Makurira, H., Mul, M.L., Vyagusa, N.F., Uhlenbrook, S., Savenije, H.H.G., 2007. Evaluation of community-driven smallholder irrigation in dry land South Pare Mountains, Tanzania; a case study of Manoo micro-dam. Phys. Chem. Earth 32, 1090–1097.

Makurira, H., Savenije, H.H.G., Uhlenbrook, S., Rockstrom, J., Senzanje, A., 2009. Investigating the water balance of on-farm techniques for improved crop productivity in rainfed systems: a case study of Makanya catchment, Tanzania. Phys. Chem. Earth 34, 93–98.

Malley, Z.J.U., Kayombo, B., Willcocks, T.J., Mtakwa, P.W., 2004. *Ngoro*: an indigenous, sustainable and profitable soil, water and nutrient conservation system in Tanzania for sloping land. Soil Till. Res. 77, 47–58.

Mando, A., Stroosnijder, L., 1999. The biological and physical role of mulch in the rehabilitation of crusted soil in the Sahel. Soil Use Manage. 15, 123–130.

Matlon, P., Kristjanson, P., 1988. Farmer's strategies to manage crop risk in the West African semi-arid tropics. In: Unger, P.W., Jordan, W.R., Sneed, T.V., Jensen, R.W. (Eds.), Challenges in Dryland Agriculture: A Global Perspective. Proceedings of the International Conference on Dryland Farming, Bushland Texas USA, August 15–19, pp. 604–606.

Mbilinyi, B.P., Tumbo, S.D., Mahoo, H.F., Senkondo, E.M., Hatibu, N., 2005. Indigenous knowledge as decision support tool in rainwater harvesting. Phys. Chem. Earth 30, 792–798.

McHugh, O.V., Steenhuis, T.S., Berihun, A., Fernandes, E.C.M., 2007. Performance of in-situ rainwater conservation tillage techniques on dry-spell mitigation and erosion control in the drought-prone North Wollo zone of the Ethiopian highlands. Soil Till. Res. 97, 19–36.

Mills, L., 2004. Evaluation of the water harvesting schemes component of the EC funded programs, IFSP 1998 and 2000 in Tigray, Ethiopia. Working Paper 1-Water Harvesting Structures. Tigray, Ethiopia.

Mokgope, K., Butterworth, J.A., 2001. Water, households and rural livelihoods; rural water supply and productive uses: a rapid survey in the Sand River catchment. WHIRL Project Working Paper 4. South Africa.

Motsi, K.E., Chuma, E., Mukamuri, B.B., 2004. Rainwater harvesting for sustainable agriculture in communal lands of Zimbabwe. Phys. Chem. Earth 29, 1069–1073.

Mugabe, F.T., 2004. Evaluation of the benefits of infiltration pits on soil moisture in semi-arid Zimbabwe. J. Agron. 3, 188–190.

Munamati, M., Nyagumbo, I., 2010. In-situ rainwater harvesting using dead level contours in semi-arid southern Zimbabwe: Insights on the role of socio-economic factors on performance and effectiveness in Gwanda District. Phys. Chem. Earth 35, 699–705.

Mupangwa, W., Love, D., Twomlow, S., 2006. Soil–water conservation and rainwater harvesting strategies in the semi-arid Mzingwane Catchment, Limpopo Basin, Zimbabwe. Phys. Chem. Earth 31, 893–900.

Myers, L.E., 1975. Water harvesting 2000 BC to 1974 AD. In: Proceedings of the Water Harvesting Symposium, Phoenix, Arizona, ARS W-22, USDA, pp. 1–7.

Nasr, M., 1999. Assessing desertification and water harvesting in the Middle East and North Africa: discussion papers on development policy. No. 10. ZEF–Bonn, Germany.

Ncube, B., Magombeyi, M., Munguambe, P., Mupangwa, W., Love, D., 2008. Methodologies in the Limpopo Basin. In: Humphreys, E., Bayot, R.S. (Eds.), Increasing the Productivity and Sustainability of Rainfed Cropping Systems. Tamala, Ghana, September 2008, pp. 209–221.

Ngigi, S.N., 2003. Rainwater Harvesting for Improved Food Security. Promising Technologies in the Greater Horn of Africa. Greater Horn of Africa Rainwater Partnership (GHARP), Nairobi, Kenya.

Ngigi, S.N., Savenije, H.H.G., Rockstrom, J., Gachene, C.K., 2005. Hydro-economic evaluation of rainwater harvesting and management technologies: farmers‘ investment options and risks in semi-arid Laikipia district of Kenya. Phys. Chem. Earth 30, 772–782.

Niemeijer, D., 1998. Soil nutrient harvesting in indigenous water harvesting in Eastern Sudan. Land Degrad. Dev. 9, 323–330.

Nyamudeza, P., Jones, E., 1994. The effects of growing sorghum (*Sorghum bicolor*) in furrows and on flat at three populations and three row widths in a semi-arid region of Zimbabwe. 2. Soil water regime throughout the season. Zimbabwe J. Agric. Res. 31, 11–21.

Nyssen, J., Haile, M., Moeyersons, J., Poesen, J., Deckers, J., 2000. Soil and water conservation in Tigray (Northern Ethiopia): the traditional *daget* technique and its integration with introduced techniques. Land Degrad. Dev. 11, 199–208.

Nyssen, J., Poesen, J., Gebremichael, D., Vancampenhout, K., D'aes, M., Yihdego, G., Govers, G., Leirs, H., Moeyersons, J., Naudts, J., Haregeweyn, N., Haile, M., Deckers, J., 2007. Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. Soil Till. Res. 94, 151–163.

Nyssen, J., Govaerts, B., Araya, T., Cornelis, W.M., Bauer, H., Haile, M., Sayre, K., Deckers, J., 2011. The use of the *marasha* ard plough for conservation agriculture in Northern Ethiopia. Agron. Sustain. Dev. 31, 287–297.

Okoba, B., Altshul, H., Tengberg, A., Twomlow, S., Ellis-Jones, J., 1998. Conserve water to save soil and the environment: an evaluation of indigenous soil and water management systems in Mbere district. SRI Report No. IDG/98/16, p. 80.

Osman-Elasha, B., Goutbi, N., Spanger-Siegfried, E., Dougherty, B., Hanafi, H., Zakieldeen, S., Sanjak, A., Atti, H.A., Elhassan, H.M., 2006. Adaptation strategies to increase human resilience against climate variability and change: lessons from the arid regions of Sudan. AIACC Working Paper No. 42. <http://www.aiaccproject.org> (accessed 08.06.11).

Otieno, D.O., Schmidt, M.W.T., Kinyamario, J.I., Tenhunen, J., 2005. Responses of *Acacia tortilis* and *Acacia xanthophloea* to seasonal changes in soil water availability in the savannah region of Kenya. J. Arid Environ. 62, 377–400.

Ouédraogo, E., Stroosnijder, L., Mando, A., Brussaard, L., Zougmore, R., 2007. Agroecological analysis and economic benefit of organic resources and fertiliser in till and no-till sorghum production after a 6-year fallow in semi-arid West Africa. Nutr. Cycl. Agroecosyst. 77, 245–256.

Oweis, T., Hachum, A., 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agric. Water Manage. 80, 57–73.

Oweis, T., Hachum, A., Kijne, J., 1999. Water harvesting and supplemental irrigation for improved water use efficiency in dry areas. SWIM Report 7, IWMI and ICARDA, IWMI, Colombo, Sri Lanka, pp. 41.

Oweis, T., Prinz, D., Hachum, A., 2001. Water harvesting: indigenous knowledge for the future of the drier environments. ICARDA, Aleppo, Syria, pp. 40.

Oweis, T., Hachum, A., Bruggeman, A., 2004. Indigenous Water-Harvesting Systems in West Asia and North Africa. ICARDA, Aleppo, Syria.

Postel, S.L., 2000. Entering an era of water scarcity: the challenges ahead. Ecol. Appl. 10, 941–948.

Raes, D., Kafiriti, E.M., Wellens, J., Deckers, J., Maertens, A., Mugogo, S., Dondeyne, S., Descheemaeker, K., 2007. Can soil bunds increase the production of rainfed lowland rice in South Eastern Tanzania? Agric. Water Manage. 89, 229–235.

Reij, C., Scoones, I., Toulmin, C., 1996. Sustaining the Soil: Indigenous Soil and Water Conservation in Africa. Earthscan, London.

Reij, C., Tappan, G., Smale, M., 2009. Agro-environmental transformation in the Sahel: another kind of – Green Revolution. IFPRI Discussion Paper.

Rijsberman, F.R., Manning, N., 2006. Beyond more crop per drop: water management for food and the Environment. Fourth water forum 16–22 March, 2006, Mexico. <http://:www.unwater.org/downloads/Beyondmorecropperdrop.pdf> (accessed 10.01.10).

Rockstrom, J., 2003. Water for food and nature in drought-prone tropics: Vapor Shift in rainfed agriculture. Philos. Trans.: Biol. Sci. 358, 1997–2009.

Rockstrom, J., Jansson, P.-E., Barron, J., 1998. Seasonal rainfall partitioning under runon and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modeling. J. Hydrol. 210, 68–92.

Rockstrom, J., Barron, J., Fox, P., 2002. Rainwater management for increased productivity among smallholder farmers in drought prone environments. Phys. Chem. Earth 27, 949–959.

Rockstrom, J., Folke, C., Gordon, L., Hatibu, N., Jewitt, G., de Vries, P.F., Rwehumbisa, F., Sally, H., Savenije, H., Schulze, R., 2004. A watershed approach to upgrade rainfed agriculture in water scarce regions through Water System Innovations: an integrated research initiative on water for food and rural livelihoods in balance with ecosystem functions. Phys. Chem. Earth 29, 1109–1118.

Rockstrom, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, L., Barron, J., Mutua, J., Damgaard-Larsen, S., 2009. Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. Soil Till. Res. 103, 23–32.

Rosegrant, M.W., 1997. Water resources in the twenty-first century: challenges and implications for action. Food, agriculture and the environment. Discussion Paper 20, IFPRI, Washington.

Sachs, J.D., McArthur, J.W., Schmidt-Traub, G., Kruk, M., Bahadur, C., Faye, M., McCord, G., 2004. Ending Africa's poverty trap. Brook. Papers Econom. Activity 1, 117–240.

Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 014010 (8pp).

Senkondo, E.M.M., Msangi, A.S.K., Xavery, P., Lazaro, E.A., Hatibu, N., 2004. Profitability of rainwater harvesting for agricultural production in selected semi-arid areas of Tanzania. J. Appl. Irrig. Sci. 39, 65–81.

Shiferaw, M., 2006. Keeping a eye on decentralization and specification of a resource policy: an overview of the policy study to the promotion of rainwater harvesting. Best practices and technologies for small-scale agricultural water management in Ethiopia. In: Proceedings of a MoARD/MoWR/USAID/IWMI Symposium and Exhibition Held, 7–9 March, Addis Ababa, Ethiopia.

Shiklomanov, A.I., 1998. World Water Resources: A New Appraisal and Assessment for the 21st Century. UNESCO, Paris.

Shiklomanov, I.A., 2000. Appraisal and assessment of world water resources. Water Int. 25, 11–32.

Siegert, K., 1994. Introduction to water harvesting: some basic principles for planning, design and monitoring: water harvesting for improved agricultural production. In: Proceedings of the FAO Expert Consultation, Cairo, Egypt, November 1993, Rome, FAO, Italy, pp. 9–22.

Sivakumar, M.V.K., 1988. Predicting rainy season potential from the onset of rains in southern Sahelian and Sudanian climatic zones of West Africa. Agric. Forest Meteorol. 42, 295–305.

Slegers, M.F.W., 2008. Farmers' perceptions of rainfall and drought in semi-arid central Tanzania. J. Arid Environ. 72, 2106–2123.

Slingerland, M.A., Stork, V.E., 2000. Determinants of the practice of Zai and mulching in north Burkina Faso. J. Sustain. Agric. 16, 53–76.

Spaan, W., 2003. Consuming the savings: water conservation in a vegetation barrier system at the Central Plateau in Burkina Faso. Tropical Resources Management Papers 42, pp. 14.

Spaan, W., Sikking, A.F.S., Hoogmoed, W.B., 2005. Vegetation barrier and tillage effects on runoff and sediment in an alley crop system on a Luvisol in Burkina Faso. Soil Till. Res. 83, 194–203.

Sterk, G., Riksen, M., Gossens, D., 2001. Dry land degradation by wind erosion and its control. Ann. Arid Zone 40, 351–367.

Stewart, J.I., 1988. Response farming in rainfed agriculture. World hunger alleviation through response farming, Davis, CA.

Stewart, J.I., 1991. Principles and performance of response farming. In: Muchow, R.C., Bellamy, J.A. (Eds.), Climatic Risk in Crop Production. C.A.B. International, Willingford, UK.

Stewart, B.A., Steiner, J.L., 1990. Water-use efficiency. Adv. Soil Sci. 13, 151–173.

Stroosnijder, L., 2007. Rainfall and land degradation. In: Sivakumar, M.V.K., Ndiang'ui, N. (Eds.), Climate and Land Degradation. Springer, pp. 167–195.

Stroosnijder, L., 2009. Modifying land management in order to improve efficiency of rainwater use in the African highlands. Soil Till. Res. 103, 247–256.

Stroosnijder, L., Hoogmoed, W.B., 1984. Crust formation on sandy soils in the Sahel II: tillage and its effects on the water balance. Soil Till. Res. 4, 321–337.

Sturdy, J.D., Jewitt, G.P.W., Lorentz, S.A., 2008. Building an understanding of water use innovation adoption processes through farmer-driven experimentation. Phys. Chem. Earth 33, 859–872.

Svendsen, M., Ewing, M., Msangi, S., 2009. Measuring irrigation performance in Africa. IFPRI Discussion Paper, International Food Policy Research Institute.

Tabor, J.A., 1995. Improving crop yields in the Sahel by means of water-harvesting. J. Arid Environ. 30, 83–106.

Taddesse, G., Peden, D., Abiye, A., Wagnew, A., 2003. Effect of manure in grazing lands in Ethiopia, East African highlands. Mountain Res. Dev. 23, 156–160.

Tadross, M.A., Hewitson, B.C., 2005. The inter-annual variability of the onset of the maize growing season over South Africa and Zimbabwe. J. Clim. 18, 3356–3372.

Temesgen, M., 2007. Conservation Tillage Systems and Water Productivity Implications for Smallholder Farmers in Semi-arid Ethiopia. PhD thesis. Taylor & Francis/Balkema, Leiden, The Netherlands.

Tengberg, A., Ellis-Jones, J., Kiome, R., Stocking, M., 1998. Applying the concept of agrodiversity to indigenous soil and water conservation practices in eastern Kenya. Agric. Ecosyst. Environ. 70, 259–272.

Tesfai, M., Stroosnijder, L., 2001. The Eritrean spate irrigation system. Agric. Water Manage. 48, 51–60.

Tsubo, M., Walker, S., 2007. An assessment of productivity of maize grown under water harvesting system in a semi-arid region with special reference to ENSO. J. Arid Environ. 71, 299–311.

Twomlow, S., Urolov, J.C., Jenrich, M., Oldrieve, B., 2008. Lessons from the field – Zimbabwe's conservation agriculture task force. Journal of SAT Agricultural Research 6 – ICRISAT. <http://www.ICRISAT.org> (accessed 12.06.11).

UNCCD, 2009. United Nations Convention to Combat Desertification: Benefits of Sustainable Land Management. World Overview of Conservation Approaches and Technologies (WOCAT), University of Berne, Switzerland.

UNDP, 2007. United Nations Development Program: Climate Change and Human Development in Africa: Assessing the Risks and Vulnerability of Climate Change in Kenya, Malawi and Ethiopia. Draft Report by ICPAC, May, 2007.

UNEP, 2009. Rainwater Harvesting: A Lifeline For Human Well-being – A Report Prepared for UNEP by Stockholm Environment Institute, UNEP. ISBN: 978-92-807-3019-7.

Walker, S., Tsubo, M., Hensley, M., 2005. Quantifying risk for water harvesting under semiarid conditions. Part II. Crop yield simulation. Agric. Water Manage. 76, 94–107.

Welderufael, W.A., Le Roux, P.A.L., Hensley, M., 2008. Quantifying rainfall-runoff relationships on the Dera calcic fluvic Regosol ecotope in Ethiopia. Agric. Water Manage. 95, 1223–1232.

Winnaar, G., Jewitt, G.P.W., Horan, M., 2007. A GIS-based approach for identifying potential runoff harvesting sites in the Thukela River basin, South Africa. Phys. Chem. Earth 32, 1058–1067.

Wiyo, K.A., Kasomekera, Z.M., Feyen, J., 1999. Variability in ridge and furrow size and shape and maize population density on small subsistence farms in Malawi. Soil Till. Res. 51, 113–119.

WOCAT, 2007. In: Liniger, Hanspeter, Critchley, William (Eds.), Where the Land is Greener – Case Studies and Analysis of Soil and Water Conservation Initiatives Worldwide. FAO, Rome.

WOCAT, 2010. WOCAT database on SLM technologies and SLM approaches. <www.wocat.net> (accessed 13.04.10–13.06.10).

Wondimkun, Y., Tefera, M., 2006. Household water harvesting and small scale irrigation schemes in Amhara Region: best practices and technologies for small-scale agricultural water management in Ethiopia. In: Proceedings of a MoARD/MoWR/USAID/IWMI Symposium and Exhibition Held, 7–9 March, Addis Ababa, Ethiopia.

Zougmore, R., Guillobez, S., Kambou, N.F., Son, G., 2000. Runoff and sorghum performance as affected by the spacing of stone lines in the semi-arid Sahelian zone. Soil Till. Res. 56, 175–183.

Zougmore, R., Zida, Z., Kambou, N.F., 2003a. Role of nutrient amendments in the success of half-moon soil and water conservation practice in semiarid Burkina Faso. Soil Till. Res. 71, 143–149.

Zougmore, R., Mando, A., Ringersma, J., Stroosnijder, L., 2003b. Effect of combined water and nutrient management on runoff and sorghum yield in semiarid Burkina Faso. Soil Use Manage. 19, 257–264.

Zougmore, R., Mando, A., Stroosnijder, L., Ouédraogo, E., 2004. Economic benefits of combining soil and water conservation measures with nutrient management in semi-arid Burkina Faso. Nutr. Cycl. Agroecosyst. 70, 261–269.