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Evaluation of small scale water harvesting techniques for semi-arid environments

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ABSTRACT

Water harvesting is widely practiced and is expected to improve water availability for domestic and agricultural use in semi-arid regions. New funds are becoming available to stimulate the implementation of water harvesting projects. We review the literature to gain insight regarding characteristics that describe and determine the success of selected water harvesting techniques. We assemble a database containing key characteristics of water harvesting techniques, based on studies published in scientific journals and in reports of international organisations. In addition to the literature also information obtained from practitioners is considered. Physical characteristics, costs, and governance needs of the different techniques are evaluated. Results show that large water harvesting structures (>500 m^3) are less expensive than small structures, when taking into account investment costs, storage capacity and lifetimes. Their costs are comparable to the costs of large scale reservoirs. The governance, technical knowledge and initial investment, are, however, more demanding for the larger structures than for smaller structures. To support the implementation of water harvesting projects in selecting appropriate techniques, we present a decision framework for choosing water harvesting techniques based on case-specific characteristics. This framework can also be used when reporting and evaluating the performance of water harvesting techniques.

1. Introduction

Global water demand has been rising over the past century (Kummu et al., 2010) and is projected to further increase due to population growth and the need for increased food production (De Fries and Rosenzweig, 2010). Part of this increase will take place in already water scarce regions (Rockström et al., 2007). In many semi-arid regions precipitation is sufficient for sustaining human habitation, but the high spatial and temporal distribution of rainfall leads to periods of water shortages. Rainy seasons are often separated by long dry periods, leading to water stress for the local population.

Climate change is expected to cause a more variable climate in semi-arid regions, leading to an increase in the frequency of droughts and more intense precipitation events (Christensen et al., 2007; Kundzewicz et al., 2007; IPCC, 2012). Climate change will negatively affect the production of agricultural crops in sub-Saharan Africa (Schlenker and Lobell, 2010), directly affecting malnutrition (Jankowska et al., 2012). Under such variable conditions, the storage of excess water during the wet season can increase local water availability during dry periods. This helps in mitigating the negative effects of intra-seasonal dry spells and bridging the dry seasons, for instance by improving the agricultural productivity of subsistence farmers (Molden et al., 2003). All small scale schemes for concentrating, storing and collecting surface runoff for domestic or agricultural uses are named water harvesting (Siegert, 1994). These water harvesting techniques are also good options to help local communities in developing countries to adapt to the expected impacts of climate change on water resources (Howden et al., 2007; Wisser et al., 2010; Lasage et al., 2015).

For sparsely populated regions water harvesting measures contribute to reaching one of the targets of Millennium Development Goal 7 (reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation). It is very likely that the adaptation fund that became operational under the Kyoto protocol (UNFCCC, 2009) will have increasing funds available over the coming years. The fund will finance adaptation programmes and projects in vulnerable developing countries. For arid and semi-arid regions many of these adaptation projects will

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have a focus on water resources. These international programmes have led to increased attention and increased availability of funding for water harvesting projects.

Many communities in arid and semi-arid regions have been harvesting water for many years (Bruins et al., 1986). Examples of water harvesting structures built thousands of years ago are known from the Babylonians, Israel, Tunisia, China and the America's (Frasier, 1980; Boers and Ben-Asher, 1982; Li, 2000; Ouessar et al., 2004). Such structures have received renewed attention with the implementation of policies to increase food production since the droughts and food crises in sub-Saharan Africa in the 1970s and 1980s (Critchley et al., 1991; Prinz and Singh, 1999; Kunze, 2000; Ouessar et al., 2004). Differences in the definition of water harvesting across the literature mostly relate to the purpose of water storage, the type of storage, and whether the source of water is in situ or ex situ (Frasier, 1980; Boers and Ben-Asher, 1982; Boers, 1994; Kahinda et al., 2007; van der Zaag and Gupta, 2008; Pachpute et al., 2009; Rockström et al., 2010). In this paper we use a definition of water harvesting based on Siegert (1994): water harvesting includes 'all small scale schemes for concentrating, storing and collecting surface run-off water in different mediums, for domestic or agricultural uses'. We focus on small scale artificial schemes up to 5000 m^3, which are constructed in semi-arid and arid areas, with average yearly precipitation up to 1200 mm. These schemes are technically easy to construct, make use of local labour, and need little to no investments from external sources, making them suitable for developing countries. They include single bunds around a tree or crop, (open) reservoirs, and both surface and sub-surface dams, with storage capacities up to 5000 m^3. Natural retention of water and water harvesting through improved landscape management are also reported in the literature (Knoop et al., 2012), but are not included in this analysis.

A water harvesting system should be chosen and designed for the local circumstances, taking into account the purpose of water harvesting, available funds, technical expertise, and the physical surroundings (Frasier, 1980; Oweis et al., 1999; Kunze, 2000; Kahinda et al., 2007; Kato et al., 2008). The objective of this paper is, therefore, to present an evaluation of a range of different water harvesting systems, including a characterisation of their application. These findings, summarised in a decision framework, are intended to support decision makers and practitioners in choosing an appropriate technique, adapted to the local needs and context. Supporting such decisions can contribute to an effective use of available funds.

2. Data and methods

2.1. Approach

We review the peer reviewed literature to identify the characteristics that determine the success of water harvesting techniques in least developed countries. In addition, we assemble a database containing values for these characteristics, using information gained from the literature and from reports of international organisations (e.g. ILRI, FAO, etc.). We use the database to: 1) Analyse which techniques are suitable for meeting domestic, livestock, or agricultural water demands; and 2) Quantify the requirements and benefits of the water harvesting techniques. For techniques improving water availability for domestic use and livestock, we also compare the results with information from implementing organisations such as NGOs and funding agencies that frequently apply and evaluate small-scale water harvesting techniques. We then propose a decision framework to support people and organisations involved in implementing water harvesting projects in choosing appropriate techniques. A full overview of all literature and other data sources used is provided in the Supplementary Material.

2.2. Classification of techniques

We consider many of the water harvesting and storage techniques that are applicable in arid and semi-arid regions. We classify water harvesting techniques into groups on the basis of their size and the way in which water is stored (e.g. container, soil, or reservoir), following Rockström (2000). Size is chosen to distinguish techniques that can be implemented individually on a household level from techniques that should be implemented collectively at community level. If a method can be implemented individually, adoption and replication is expected to be easier. Whether a technique stores water in a container or reservoir, or stores water in the soil (as groundwater or soil moisture) has implications for evaporation and for the possible uses of the water.

The combination of these two sets of characteristics leads to four separate groups: small measures for soil water conservation, small measures storing extractable water in a container, large measures storing extractable water in the soil, and large measures storing extractable water in a reservoir (Table 1).

2.3. Characteristics

To enable a reliable selection of a water harvesting technique that are sustainable under local circumstances, it is necessary to review the characteristics of the different techniques. The characteristics we consider cover the main factors determining the applicability of water harvesting projects, which are physical (hydrologic, terrain, and technical), cultural (acceptability), and socio-economic (institutional and economic) in nature (Critchley et al., 1991; Kunze, 2000; De Graaff et al., 2002; Stroosnijder, 2003; Fox et al., 2005; Ngigi et al., 2005; Bewket, 2007; Lasage et al., 2008; Tumbo et al., 2011).

The water harvesting measures should technically be applicable under the physical circumstances in the field. However, it is also important to account for the cultural acceptance of the technique and the need for complex governance after implementation. Governance is necessary if available water needs to be shared by many people in one village, or in case the water needs to be shared between several villages. There are many examples of water harvesting projects that have failed to meet targets due to complexity of governance, or because they were not acceptable to the population as result of cultural, environmental, or economic conditions (Herweg and Ludi, 1999; Bewket, 2007; Fekadu et al., 2007; Kato et al., 2008; Abebe et al., 2012). The resources necessary for construction (physical, labour, knowledge, capital) and their effects on the surrounding environment and hydrologic conditions (quantity and quality) also need to be taken into account. Water quality is especially important when a structure provides water for domestic use. Water quality is less relevant when the water is used only for irrigation.

Table 2 lists the physical and socio-economic characteristics relevant to water harvesting techniques. The analysis in Section 3 uses several of these characteristics as indicators, or combines characteristics to form new indicators. We define indicators as characteristics that are used to support the comparison or selection of techniques. Combined indicators are, for example, investment costs in relation to the water yield of the structure. We consider two indicators for the initial investment: 1) The cost per m^3 of storage, and, 2) The cost of water stored over the lifetime of the structure. We calculate the latter indicator using the initial investment and total amount of water that will be stored by the structure over its lifetime, assuming the storage will be filled one time per year. This assumption was made for pragmatic reasons as we have gathered

Table 1
Description of water harvesting techniques included in the review.

Small storage in container	
Rain jar	Small tank, capacity 0.2 m^3–6 m^3, storing water harvested from the roof, made of reinforced cement (e.g. chicken wire). Water is extracted from the tank using a tap. Larger tanks need a foundation (Pinfold et al., 1993).
Ferro cement tank	Above ground tank including a tap, capacity 3 m^3–15 m^3 storing water collected from a catchment area like a roof. Made of ferro-cement that consists of a thin sheet of cement mortar reinforced with wire mesh and steel bars. Ferro cement components can be casted in any shape and can be constructed by semi-skilled labourers (NWP, 2007).
Stone masonry tank	Above ground tank including a tap, capacity 3 m^3–20 m^3 storing water collected from a catchment area like a roof. The structure is built using stone masonry and made water tight using cement mortar; can be constructed by semi-skilled labourers (NWP, 2007; Dale, 2010).
Larger storage in container	
Open reservoir	Natural or (hand) dug open reservoir to store water collected from elsewhere. The permeability of the pond can be reduced by using lining (concrete or plastic). Sizes vary from 30 m^3 (individual household use) to 20,000 m^3 (community use). Simple structure that can be constructed by non trained labourers. When lining is used, some expertise is necessary. Water is extracted using a bucket, foot pump, or motor pump (Fox et al., 2005; Critchley, 2009).
Cistern	Man-made underground reservoirs of various shapes and geometry, storing water collected from a surface plot, capacity 5 m^3–100 m^3. Construction materials are concrete blocks or stone masonry for the walls and bottom, cover materials can be corrugated iron plates, mortar or concrete. Water is extracted using a hand pump or bucket (Biazin et al., 2012)
Small in-soil storage measures	
Contour trenches or ridges	Small trenches or ridges 1.5–3 m apart, following the contours of the landscape. Aims to increase infiltration. Low investment, low durability, require yearly maintenance (Li et al., 2000; Mugabe, 2004; Adgo et al., 2013)
Terraces	Unit consisting of a relatively steeply faced structure across the slope (a riser, bund, bank, dyke, ridge, wall, embankment, etc.) supporting a relatively flat terrace bed. Aims to increase infiltration, storage in the soil and reduced erosion. A subdivision is based on the material used for the bund, as this influences the construction costs (soil bunds, fanyaa juu, and stone bunds) (WOCAT, 2007; Rockström, 2000)
Large in-soil storage measures	
Spate irrigation	Pre-planting, diversion of floodwaters (spate floods) from beds of ephemeral rivers by free intakes, by diversion spurs or by bunds, that are built across the river bed, to spread over large areas as irrigation water and to be partially stored in the soil. An uncertain method, as it is dependent on the occurrence of floods. The structure often needs to be rebuilt after a flood (Tesfai and de Graaff, 2000; van Steenbergen et al., 2011)
Sub-surface dam	Dam built in a river bed of seasonal river. The dam is based on an impermeable layer to create an artificial aquifer, to be filled by intercepted groundwater. The dam can be constructed of clayey soil, stone masonry or concrete. Wells can be used to abstract the stored water from the aquifer. Instead of storing the water in surface reservoirs, water is stored underground. The main advantage is that evaporation losses are much less for water stored underground and the risk of contamination is reduced (Nissen-Petersen, 2006).
Sand dams	Impermeable concrete or stone masonry structures constructed across seasonal rivers. Increasing water storage capacity, by enlarging the aquifer above the original river bed, through accumulation of sand and gravel particles against the dam. The sub-surface reservoir is recharged during flash floods and when the reservoir is filled surplus water passes the dam. The stored water is captured for use through digging a scooping hole, or constructing an ordinary well or tube well. By storing the water in the sand, it is protected against high evaporation losses and contamination (Lasage et al., 2008)

information from numerous sites with differences in intensity and frequency of rainfall, occurrence of drought years, and number of rainy seasons. Hence, the number of times a structure is replenished differs between sites and years. To avoid making arbitrary choices on replenishment, we use the conservative estimate of one replenishment per year. If the storage fills more than one time per year the actual costs per m^3 will be lower. When local circumstances are known more exact calculations can be made.

The effective storage capacity is a combination of three characteristics: storage capacity, evaporation, and seepage. Seepage may lead to beneficial downstream effects, such as groundwater recharge. However, the water is not available at the location where the water harvesting structure is placed. Hence, we consider seepage to be a loss for the water harvesting system.

We calculate the costs and benefits of the structures in terms of US dollars in 2009. We use daily wage rates of US$ 10.00 and US$ 2.00 for trained and untrained labour, respectively. The benefits are calculated assuming one harvest of water per year, as we assume that storage takes place one time per year.

3. Results

We divide the water harvesting techniques into two groups, according to size: household and communal structures. We considered 85 articles and reports in developing the summary that appears in Table 3 (See also the Supplementary Materials). For each of the water harvesting techniques, up to thirteen sources contain relevant information and this number varies between the indicators. For household level techniques less information is available than for communal techniques. Although the literature was reviewed for all characteristics listed in Table 2, not all of them are included in Table 3. For example, we found little or no information in the literature regarding impacts on households, the surrounding environment, and health.

The relative range and standard deviation of indicator values reported is highest for stone masonry structures. For all techniques, the range of values reported for *effective storage capacity* is relatively largest. Ferro-cement tanks are smaller than stone masonry tanks, while sand dams are the largest systems. Open reservoirs and cisterns are on average the same size. *Construction costs* are calculated to 2009 US dollars. Only rain jars need limited investments, on average US$ 44 per unit. All other techniques require an investment between US$ 2000 and US$ 12,000. Cisterns and open reservoirs are cheaper than both types of household tanks, even though they have larger storage capacities. These differences in price are due to the type of catchment area, the investment for corrugated iron plates included in the costs for household tanks, and the low needs for investments for ground catchments of cisterns and open reservoirs. *The price* per m^3 shows the same: household structures are more expensive per m^3 than communal structures. When the designed lifetime of the structures is also taken into account, the difference in price per m^3 between both types of structures increases even further. Sand dams need an investment of US$ 0.40 per m^3 over their lifetime compared with US$

Table 2
Characteristics of water harvesting techniques.

	Indicator	Description	Unit/class
Physical characteristics			
Field preconditions	Slope of terrain	Range of slopes where technique is applicable	%
	Minimal precipitation	Minimal average yearly precipitation necessary for technique	mm
	Maximal precipitation	Maximal average yearly precipitation, above which the technique becomes less efficient due to water logging for example	mm
	Impacts on surrounding environment	Partition of total available water stored by the technique	%
		Need for clearing vegetation	−/0/+
	Availability of a catchment	The minimal size of the catchment necessary to fill the reservoir under site specific conditions	m^2
Characteristics of structure	Storage capacity	Maximal amount of water that can be stored	m^3
	Evaporation	Amount of stored water that evaporates before it can be used	%
	Seepage	Amount of stored water that is lost through seepage before it can be used	%
	Effective storage capacity	Total amount of water that is stored and available for use in one year, taking into account loss through evaporation and seepage. Based on the assumption that the structure is filled one time to full capacity, and no additional storage occurs during the rainy season.	m^3
	Water quality	The relative quality of the water stored.	−/0/+
Socio-economic characteristics			
Resources necessary	Investment costs	Financial resources needed for the construction of the measure concerted to US$ 2009 value	US$ (standardised to 2009 value)
	Local labour	Total number of unskilled labour days necessary for the construction of the measure	Days
	Skilled labour	Total number of skilled labour days necessary for the construction of the measure	Days
	Materials	Type of material necessary for construction, local available versus materials that need to be brought to the location like: cement, concrete, wire, stones.	Local/external
	Technical complexity	The need for technical assistance during construction from an NGO or government organisation.	Simple/medium/complex
	Governance	What type of governance structure is necessary, none, water resources committee	None/water users association/water resources committee
	Maintenance	Amount of money (in 2009 US$) and# of man days that are necessary for maintenance per year	US$ (standardised to 2009 value) Days
Impacts	Health	The risk of an increase in vector borne diseases, small, medium or large.	Low/medium/high
	Change in crop yield	% change in yield for agricultural crops	%
		Change in yield	US$/ha (standardised to 2009 value)
	Change in livestock production	Change in number of animals, or in production per animal	US$ (2009)
	Change in household characteristics	Change in school attendance, type of employment	
Other	Lifetime of structure	# of years the structure will be in use	Years

8.73 per m^3 over the lifetime of ferro-cement tanks. For this indicator the range of values for a single technique varies from a factor 3 for rain jars, to 20 for ferro cement tanks, cisterns, open reservoirs and sand dams, and up to 135 for stone masonry tanks. The contribution of the community to the total investment varies from 15% (rain jar) to 50% (sand dam). The other techniques have community contributions between 32% and 42%. Sand dam construction requires simple manual labour which can be done by the local communities, leading to a high community contribution in comparison to other techniques. The range and standard deviation for the community contribution is low, compared to the characteristics described above. *Maintenance costs* are not often mentioned. Table 3 has no information for maintenance costs of household techniques. For community techniques information is based on a few sources only. Open reservoirs have highest maintenance costs due to repairs of the sealant. Cisterns have a roof protecting the sealant and are mostly sealed with cement or stone masonry, where open reservoirs often have plastic as a sealant. In general, sand dams do not need maintenance, except for the hand pump installed in the reservoir. These maintenance costs are limited and less than the 5% to 10 % of the construction costs per year, based on a rule of thumb used by practitioners (Batchelor et al., 2011; Moges et al., 2011).

For the indicators *Slope* and *Yearly precipitation*, the minimum and maximum values found are reported to indicate the range of conditions under which these techniques have been implemented. For sand dams the role of slopes has been studied quite intensively, whereas for cisterns only a minimum slope value was found in literature. *Materials* lists all materials that are normally used in the construction. The local availability of these materials is a determinant of the logistic complexity of the project and indicates the possibilities of local actors to adopt the technology without outside support. Only rain jars can be constructed using local materials, the other techniques need at least cement and most often also wire and concrete.

The values for the indicators *Technical complexity* and *Water quality* are expert judgements of the author, based on literature and field observations of the author in Ethiopia, Ghana, Kenya, Peru and Vietnam. Structures that use reinforced concrete (ferro-cement tanks, cisterns and sand dams) need skilled people, thus leading to increased complexity of construction. Open reservoirs and stone cement tanks need a mason. As many projects train local people to become masons a medium high value is assigned for complexity. If an open reservoir uses plastic or termite soil as sealant, it is judged simple. For rain jars several successful examples are available of projects where local people were trained to make the jars from

Table 3
Indicator values for container storage water harvesting structures for domestic water use based on review of the literature (see supplementary material).

Indicator	Household structures			Communal structures		
	Rain jar	Ferro cement tank	Stone masonry tank	Cistern	Open reservoir	Sand dam
Effective storage capacity (m^3)	Avg: 0.92 Range: 0.5 to 1.5 SD: 0.52, N = 3	Avg: 19 Range: 3 to 39 SD: 16, N = 6	Avg: 60 Range: 5 to 240 SD: 92, N = 6	Avg: 133 Range: 30 to 1000 SD: 261, N = 13	Avg: 144 Range: 30 to 300 SD: 90, N = 9	Avg: 1027 Range: 197 to 2678 SD: 913, N = 10
Construction costs (US$, 2009)[a]	Avg: 44 Range: 40 to 48 SD: 4, N = 3	Avg: 3371 Range: 65 to 12,961 SD: 4951, N = 6	Avg: 7610 Range: 41 to 24,084 SD: 9036, N = 6	Avg: 2324 Range: 185 to 9932 SD: 2733, N = 13	Avg: 2045 Range: 440 to 6389 SD: 2136, N = 9	Avg: 11,896 Range: 858 to 24,609 SD: 8581, N = 10
US$/$m^3$	Avg: 59.56 Range: 27 to 88 SD: 31, N = 3	Avg: 132 Range: 13 to 332 SD: 126, N = 6	Avg: 220 Range: 7 to 770 SD: 280, N = 6	Avg: 32.28 Range: 2.18 to 112 SD: 38, N = 13	Avg: 20.47 Range: 3 to 56 SD: 21, N = 9	Avg: 19.9 Range: 2 to 48 SD: 17, N = 10
US$/$m^3$ over lifetime	Avg: 2.98 Range: 1.33 to 4 SD: 1.55, N = 3	Avg: 5.29 Range: 0.51 to 13.29 SD: 5.04, N = 6	Avg: 8.73 Range: 0.23 to 31 SD: 11.26, N = 6	Avg: 1.08 Range: 0.31 to 3.73 SD: 1.25, N = 13	Avg: 1.33 Range: 0.31 to 3.75 SD: 1.31, N = 9	Avg: 0.40 Range: 0.05 to 0.95 SD: 0.32, N = 10
Community contribution (% of total costs)[b]	Avg: 15 Range: 3 to 27 SD: 18, N = 3	Avg: 32 Range: 31 to 34 SD: 1.36, N = 4	Avg: 35 Range: 34.55 to 35.23 SD: 0.29, N = 4	Avg: 33 Range: 7 to 72 SD: 22, N = 7	Avg: 42 Range: 23 to 56 SD: 19, N = 3	Avg: 50 Range: 26 to 55 SD: 10.42, N = 9
Maintenance costs (US$/year)[a]	n.a.	n.a.	n.a.	Avg: 25 Range: 8 to 30 SD: 11, N = 4	Avg: 44 Range: 6 to 130 SD: 42, N = 7	Avg: 28 Range: 10 to 43 SD: 10, N = 9
Slope (%)	n.a.	n.a.	n.a.	1 <	1 to 11	1 to 3
Yearly prec. (mm)	100 to 800	100 to 800	100 to 800	130 to 800	up to 1200	300 to 1200
Materials	Local	Wire, cement	Local & cement	Cement, wire, iron sheets/concrete	Cement & wire	Cement, concrete & wire
Technical Complexity	Simple	Complex	Medium	Complex	Medium	Complex
Water quality	0	0	0	−/0	−	+
Governance	None	None	None/water users group	None/water users group	None/water users group	Water users group/association

[a] 2009 US$ value.
[b] Trained labour = US$ 10/day, untrained labour = US$ 2/day.

local materials (Rees et al., 2000). Expert judgement is used for water quality as common water quality indicators such as Biological Oxygen Demand (BOD) or coliform levels are not given in most articles, except for cisterns. Techniques using surface runoff as a water source are vulnerable to contamination, as animal droppings and other contaminants are flushed into the system. Sand dams are an exception, because the water is stored in sand and extracted by a hand pump. This protects and purifies the water before use (Lasage et al., 2008). Open reservoirs are exposed to the air and sun, thus resulting in lower water quality than cisterns, which are protected by a roof. Techniques using roofs as catchment area have fewer issues with contamination.

The *Governance* indicator shows that household structures are less demanding on management after their construction. For stone masonry tanks, cisterns and open reservoirs the level of governance is dependent on the size and the use by either a single household or a community. Sand dams and spate irrigation always need a water users group as they are used by several households or even multiple communities (van Steenbergen et al., 2011). In some regions water users associations manage several dams in one stream.

Figs. 1 and 2 show the relation between effective storage capacity, which is the water available for use in one year, assuming the system in filled one time to full capacity (Table 2), and investment costs, distinguishing between data from literature and those provided by NGOs. Fig. 1 shows the effective storage capacity in relation to the investment cost per m^3 of water stored over the lifetime of the structure, assuming the storage is filled once per year. Both for literature data and NGO data the regressions are significant at 0.01 level (Table 4), indicating a decrease in costs with increasing storage capacity, reflecting economies of scale. Similar relations are found for most of the individual techniques. The investments for the different techniques range from US$ 0.02 to US$ 30 per m^3 over the lifetime. The literature data shows a larger range

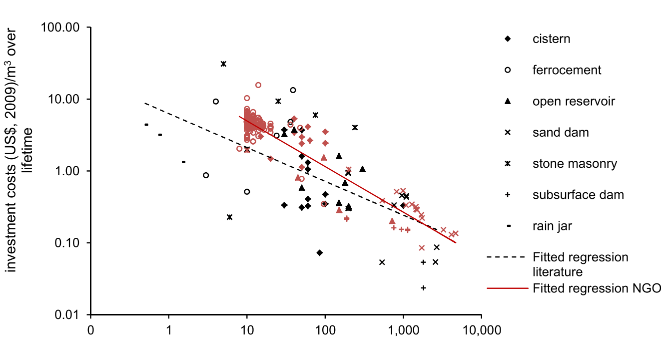

Fig. 1. Investment cost per m^3 water stored over the lifetime of the structure compared to the size of structures supplying domestic water (literature data in black and NGO in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

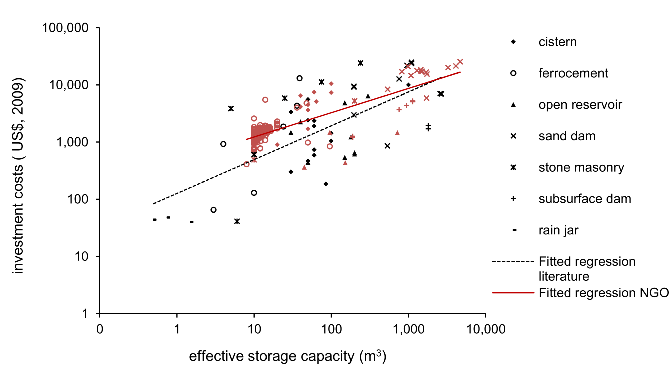

Fig. 2. Total investment costs in relation to size for structures supplying domestic water (literature data in black and NGO in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

than the NGO data.

Fig. 2 shows the relation between the effective storage capacity and the investment costs, assisting the choice of techniques under a known budget. Investment costs range from US$ 40 to US$ 25,000 mainly depending on the size of the system. The regressions are significant for both datasets (Table 4). A Chow test was performed to test if the regressions using data from the literature and NGOs differ from a lumped regression. The individual regressions are significantly different (at $p > 0.05$) from a lumped regression, due to the higher investment costs of small systems in NGO data as compared to literature data. Larger systems do not show such a difference.

In Fig. 1 the same effect is seen: smaller systems have higher per m^3 costs over their lifetime in the NGO data, than in the literature data. One possible explanation is the large number of data for ferro cement tanks in the NGO data while data for rain jars, which are small and cheap, are lacking in this dataset.

Sand dams have quite a large range in costs compared to their storage capacities. For dams it makes a difference whether they are constructed in a pastoralist society or in an agricultural society. In pastoralist societies the local communities often migrate with their herds to grazing areas, limiting the potential for local contribution of labour to the construction. The sand dam needs to be finished before the start of the rainy season so that the unfinished dam is not flushed away by a flash flood. In pastoralist societies NGOs often make use of hired labour to ensure completion in time. This leads to higher costs for construction compared to situations where local communities can contribute more to the construction.

The results of the literature review on water harvesting techniques for crop production are summarised in Table 5. Only data from literature are used in this table because NGO data was lacking for most techniques. Due to lack of information on important indicators, such as the change in yield, not all techniques could be included. Sub-surface dams and sand dams are two techniques where information is missing. Of all the papers on water harvesting techniques in crop production, only 20 papers contain information of relevance, resulting in often qualitative information.

We have recalculated some indicators into per hectare values, e.g. change in yield and the investment costs for several techniques. *Construction costs* show that techniques that store water in the soil are cheaper than techniques storing water in a container. Only open reservoirs with plastic lining have comparable investment costs to in-soil storage. On average, all techniques show a positive impact on yield ranging from 11% to 1000% *yield increase* compared to the situation where no measures are implemented. In specific cases the yield effect is negative, e.g. for terraces water logging during wet years can negatively affect crop growth.

The change in yield summarised in Table 5 is only due to increased water availability. Several studies show that increased water availability together with fertiliser application lead to even larger increases in yield (Rockström et al., 2003; Biazin et al., 2012). The data for value of *the changed yield* per *hectare over the lifetime of the structure*, including maintenance costs, show for two out of three techniques a wide range, from a negative financial effect to a very positive effect. Comparing these returns to the investment costs shows a negative return for open reservoir, cement. Soil bund terraces have a mixed result, from negative to a slightly positive return. Stone bund terraces have the largest range in values, and have, on average, the best returns of the techniques included in this study. Thus techniques storing water in the soil profile perform better than techniques storing water in a reservoir. Their investment costs are lower and their positive effects on yield are larger. We do not have yield information pertaining to other techniques, including spate irrigation, sub-surface dams, and sand dams.

Community contribution is very high for the in-soil storage techniques, reducing the investment cost considerably. The reported community contribution for container storage techniques varies between 20% and 56%. The maximum angle of the slope where terraces can be built is far steeper than for the other techniques. *Minimal yearly precipitation* needs to be higher for terraces than for other techniques. For spate irrigation it is important that precipitation occurs in a short period at high intensity, leading to floods that can be diverted to the fields. The container techniques need less water, as they store surface run-off, which can then be applied on a small field with crops. When less water is available, a smaller area is irrigated. As the area of terraces is fixed, more water is necessary to have a positive impact on yield. The values for the indicators *Technical complexity* and *Governance* are expert judgements based on literature and field experience of the author. Several techniques have a different value in Tables 3 and 5 because the application of the techniques is different (domestic use vs. agricultural use).

Table 4
Regression coefficients for the relation between investment costs (y) and storage capacity (x) based on the data shown in Figs. 1 and 2.

	Investment costs related to size		Costs per m^3 over lifetime related to size	
	R^2	Coefficients	R^2	Coefficients
Literature	0.47[a]	$y = 126.01x^{0.5918}$	0.38[a]	$y = 6.2758x^{-0.471}$
NGO	0.65[a]	$y = 458.93x^{0.4252}$	0.85[a]	$y = 21.424x^{-0.635}$

[a] Regression is significant at 0.01 for t-test and F-test.

4. Discussion

4.1. Water harvesting techniques

For a project with the goal to improve water availability for domestic or livestock use, and assuming that investment costs per m^3 over the lifetime is the main decision criterion, the analysis of 85 articles and reports provides evidence that it is best to construct large schemes. Sub-surface dams and sand dams make water available at US$ 0.04 and US$ 0.40 per m^3 on average, compared with US$ 1 to almost US$ 9 for smaller systems. For all systems these costs may be overestimated, as it is assumed that the systems are only filled one time per year. In reality they may be filled several times during one rainy season or two rainy seasons may produce enough run-off to, at least partly, fill the reservoirs. Lasage et al. (2015) show for sand dams in Ethiopia that recharge takes place five times during the year. Small systems in the field are probably replenished more often than large structures like sand dams. However, small structures need to fill at least 20 times more often than large structures to reach the same costs per m^3. The investments for sub-surface storage systems, such as sand dams and sub surface dams, are comparable to the maximum costs of US$ 0.30/m^3 for large scale reservoirs, reported in a recent study on global and regional adaptation costs (Ward et al., 2010).

If the initial investment costs for sand dams are above the available budget, or if they are not suitable for the local circumstances, cisterns appear to be the second best option. Cisterns are comparable in price to open reservoirs, but their water quality is better. Before implementing any structure, it is advisable to explore how others have built these structures. All techniques show a range in direct investment costs and cost per m^3 over the lifetime of the structure. By learning from experiences, it is possible to build cheaper structures (Machiwal et al., 2004).

Table 5
Indicator values for in-soil storage techniques and container storage techniques for crop cultivation water use based on review of the literature.

Indicator	In-soil storage techniques			Container storage techniques			
	Terrace, soil bunds	Terrace, stone bunds	Spate irrigation	Open reservoir, plastic	Open reservoir, cement	Stone masonry	Cistern
Construction costs (US$/ha)[a]	242	Avg: 2753 Range: 364 to 13,380 SD: 4,838, N = 7	n.a.	Range: 2457 to 4146	Avg: 39,026 Range: 4731 to 127,780 SD: 41,621, N = 7	187,500	Range: 17,800 to 48,000
Yield change (%)	30	Avg: 262 Range: 12 to 1000 SD: 381, N = 8	Range: 307 to 357	n.a.	Avg: 71 Range: 39 to 99 SD: 24, N = 6	n.a.	Range: 11 to 201
Yield change (US$/ha)[a]	Range: 34 to 100	Avg: 946 Range: 15 to 6570 SD: 2,273, N = 8	n.a.	n.a.	275	n.a.	n.a.
Yield change (US$/ha over lifetime)[a,b]	Range: −460 to 342	Avg: 17,847 Range: −15,120 to 143,484 SD: 51,144, N = 8	n.a.	n.a.	3495	n.a.	n.a.
Community contribution (% of total costs)	100	Avg: 100 Range: 98 to 100 SD: 1, N = 6	n.a.	49	Range: 21 to 56	Avg: 35 SD: 0 N = 4	Avg: 20 Range: 7 to 31 SD: 10, N = 4
Slope (%)	2 to 50	2 to 69	n.a.	1 to 3	1 to 3	1 to 3	1 to 3
Yearly prec. (mm)	400 to 1400	400 to 2000	50 to 750	up to 1200	up to 1200	100 to 800	130 to 800
Materials	Local	Local	Local/cement, concrete & wire	Plastic	Cement & wire	Cement, stone, wire	Cement, wire, iron sheets/concrete
Technical complexity	Simple	Medium	Medium	Simple	Medium	Complex	Complex
Governance	Simple	Simple	Complex	Simple	Simple	Simple	Simple

[a] 2009 US$ value.
[b] Including yearly maintenance.

4.2. Decision support framework

Based on the analysis of the database and insights gained from practitioners and peer-reviewed papers, we propose a decision support framework to assist people and organisations involved in implementing water harvesting projects to choose appropriate techniques (Fig. 3). This framework, together with the detailed information in Table 3, can help to achieve better informed choices. Where existing frameworks often start from a technical and physical perspective (e.g. Critchley et al., 1991; Gould and Nissen-Petersen, 1999; Rockström et al., 2007; UNEP, 2009), we based the framework on a user perspective.

The purpose of water harvesting is the entry point, determining the required quality of the water for either drinking water for humans and animals or irrigation water for crops (Zhu et al., 2004). The next step relates to the size of the system, which is dependent on the local demand. Within the set of artificial schemes which store up to 5000m^3 which are included in this assessment, we consider systems under 50 m^3 as small and those above as large. From field experience it is known that households rarely have structures above this size. Next is an evaluation of all costs that are made during the construction, including local contributions like labour. This evaluation can be used to check if available funds are sufficient to implement a certain technique, or if a farm household

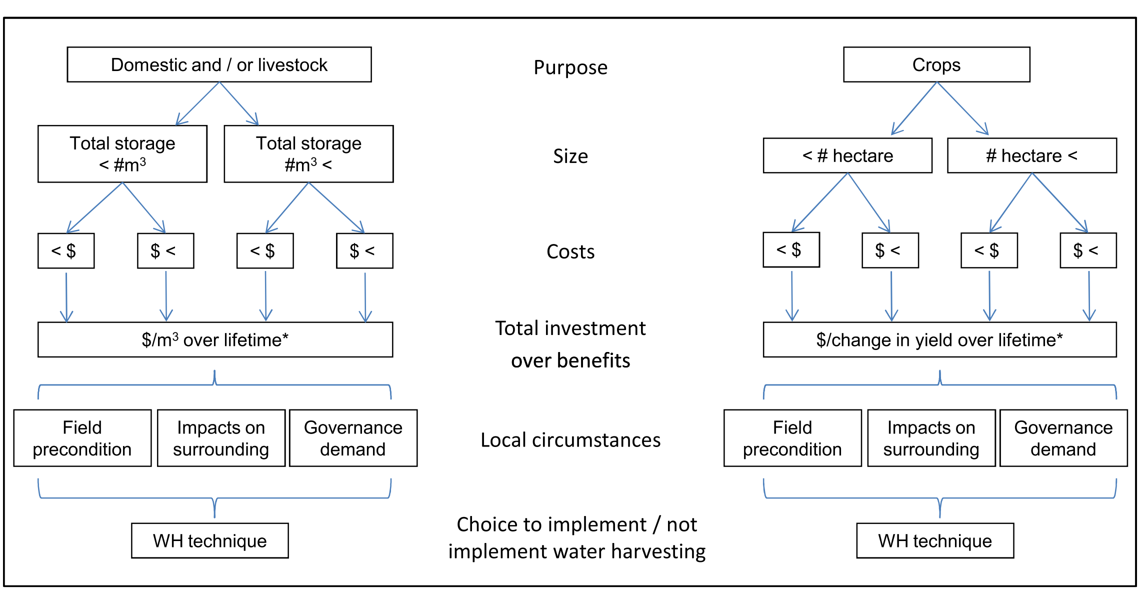

Fig. 3. Proposed decision framework for selecting water harvesting techniques.

is able to make the necessary investments, e.g. following methods as proposed by Tumbo et al. (2011). In making a cost-benefit analysis of the possible structures, total investment costs, maintenance costs, lifetime of the structure and the capacity of the structure should be included (Ghisi and Schondermark, 2013). For drinking water the unit of capacity is m^3 and for farming this is the area to which additional water can be applied. Until this stage in the decision tree all steps relate to water demand and economic performance. However, an important step in deciding the appropriate technique is to assess whether the technique fits the local circumstances. The fit with local circumstances depends on physical, economic, and socio-political dimensions (which include governance) (van der Zaag and Gupta, 2008). Using this structured approach in selecting appropriate water harvesting techniques will prevent choosing a technique based on arbitrary donor preferences not suitable to the specific location, as described by Biazin et al. (2012). It will also contribute to increase the sustainability of the measures into the future (Pachpute et al., 2009). An alternative outcome of the assessment of a water harvesting technique may be that the local conditions and investment opportunities offer too little scope for sustained benefits. Under such conditions it is better to not invest in water harvesting.

From a household perspective, an investment to increase agricultural production should ideally have a pay-back time of a few years (Tumbo et al., 2011). Based on our data we can only make a rough estimation of the pay-back time for two techniques. The data from Table 5 give average investment costs of 2753 $/ha for terrace stone bunds and yearly returns of 811 $/ha (assuming a lifetime of the structure of 22 years). For open reservoirs the average investment costs are 39,026 $/ha and the yearly returns 233 $/ha (assuming a lifetime of the structure of 15 years). For stone bunds it would take more than 3 years to pay-back the investments. Nyssen et al. (2007) conclude for their case study that the maintenance costs and the increased yield are approximately the same. In spite of this, the construction of stone bund terraces is supported by 75% of their respondents. These results indicate that other factors besides the financial benefits play a role in community support for water harvesting. Based on our data the pay-back time for open reservoir would be 167 years. This rough estimation indicates, from a financial perspective, that stone bunds could be acceptable measure for farmers to increase their yields, and that open reservoirs with cement sealing are not. Bouma et al. (2014) carried out research on the agricultural returns to investments in water harvesting, which partly uses the same database as our study. They also account for variability in the quality of the rainy season for a period of 10 years. Their research indicates that the returns to investment are on average 330 $/ha/year, which would lead to a comparable pay-back time as indicated above.

For scholars, as well as practitioners, the framework can be used as a checklist in the selection process of techniques for future projects. In addition, the framework and the tables provided in this paper enable a better comparison of techniques and their performance. Choosing a technique based on limited information and without the comparison of alternative techniques can lead to ineffective investments. In Ethiopia a large scale programme on household pond (open reservoir) construction was implemented throughout the country based on positive results in one region. The ponds were constructed in every region, ignoring differences in climate and in socio-economic circumstances. A few years after completion, approximately 75% of the ponds were non-functional in much of the country (Lasage et al., 2011; Moges et al., 2011).

4.3. Limitations

The review of literature reveals that information on characteristics and indicators related to the governance of water harvesting systems, the impacts on the surrounding environment and impacts on the socio-economic conditions of households are hardly documented. Knowledge on these characteristics is important as they influence the durability of the structures. Good performance on these aspects may offset higher investment costs. Examples are improved health due to better water quality and more and better nourishment, or higher school attendance of children when water is available at shorter distances or at school (Kahinda et al., 2007; Lasage et al., 2008; Baguma et al., 2010).

Limited to no information is available in the literature on downstream impacts of the water harvesting techniques. For a single structure such impacts are likely to be small. When many structures are built in an area, downstream impacts are more likely. More knowledge on the downstream impacts is required before replicating structures to prevent large negative effects downstream (Nyssen et al., 2010; Lasage et al., 2015). In Kenya, from 2% to 4 % of the runoff was stored after creating 500 sand dams in a catchment of 20,000 km^2 (Barron and Okwach, 2005; Aerts et al., 2007). Nyssen et al. (2010) describe how groundwater levels rose after the construction of 242 check dams in gullies, improving water availability in wells during the dry season.

Supplemental irrigation and improved water availability for crops generate the largest benefits in years with below normal rains. The additional water makes the difference between a good harvest and no harvest. In years with normal or above normal rains, the relative increase in harvest is modest or even negative, as water is not the limiting factor for the harvest (e.g. Fox and Rockström, 2000; Barron and Okwach, 2005; Kassie et al., 2008). The largest positive effects on yield are achieved in cases where integrated farm resource management is practiced, indicating that water and soil fertility should not be considered in isolation (Tabor, 1995; Oweis and Hachum, 2006). Most case studies report harvest data only for short periods and the impacts on the households are therefore limited. Future impact studies should cover longer periods that include both wet and dry years, enabling a better assessment of the impacts on production (Kunze, 2000).

Another data gap concerns the costs and benefits of measures that store water in the soil. Little new evidence has been provided since Stocking (1988) and Kunze (2000) first identified this omission. Data are unavailable for many water harvesting projects aimed at improving crop growth data. Jankowska et al. (2012) have shown that the impacts of climate change on malnutrition and livelihoods are large. Water harvesting potentially can help reducing this negative impacts. Based on the sparse evidence Bouma et al. (2014) found that water harvesting increased crop yields with 78% on average, across Asian and African case studies found in the literature, and that impacts are greatest in low rainfall years. Impacts on livelihoods are rarely mentioned in these studies and Bouma et al. (2014) indicate that economic returns are often small. More detailed reports on the impacts on livelihoods are needed to assess the likely benefits of alternative water harvesting techniques on alleviating the vulnerability of households to droughts. Making such data openly available and explicitly assessing the performance of implemented structures is not yet common for many implemented projects, limiting the evidence-base needed for ex-ante evaluation of water harvesting decisions.

5. Conclusions

The information required to evaluate the sustainability and applicability of individual water harvesting techniques is lacking in many settings. Some information is available in peer-reviewed literature and in the reports of the government agencies, institutes, and NGOs that implement water harvesting projects.

Better public access to this information would promote better design, evaluation, and selection of water harvesting projects in the future.

On the basis of the available information, we conclude that larger water harvesting structures have lower costs per unit of water captured. When accounting for the lifetime of the structure, the unit costs range from US$ 1 per m^3 to US$ 9 per m^3 for small structures, and from US$ 0.04 per m^3 to US$ 0.40 per m^3 for large structures. For smaller structures, less technical knowledge is needed, the initial investment cost is smaller, and the governance is less complex than in the case of larger structures.

Water harvesting is a suitable strategy for adapting to water shortages caused by climate change. Agencies and donors wishing to advance agricultural development must consider local circumstances and indicators of social and economic conditions when evaluating alternative investments. The information we present in Table 2 and Fig. 3 can assist them and other practitioners in focussing on pertinent characteristics. Such an approach will ensure that water harvesting projects are not considered in isolation, but as part of the integrated social, cultural, economic and physical system.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jaridenv.2015.02.019.

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