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

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A B S T R A C T

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