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Assessing the implications of water harvesting intensification on upstream–downstream ecosystem services: A case study in the Lake Tana basin

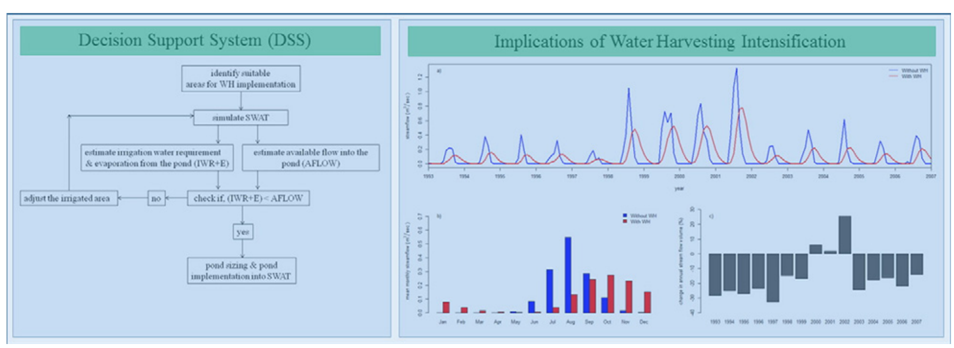
Yihun Taddele Dile [a,b,*], Louise Karlberg [b], Prasad Daggupati [a], Raghavan Srinivasan [a], David Wiberg [c], Johan Rockström [d]

[a] Spatial Sciences Laboratory in the Department of Ecosystem Sciences and Management, Texas A&M University, 1500 Research Parkway, College Station, TX 77845, USA
[b] Stockholm Environment Institute (SEI), Linnégatan 87D, Box 24218, 104 51 Stockholm, Sweden
[c] International Institute for Applied Systems Analysis (IIASA), Schlossplatz, A-2361 Laxenburg, Austria
[d] Stockholm Resilience Center, Stockholm University, 106 91 Stockholm, Sweden

HIGHLIGHTS

- Water harvesting (WH) bridges climate variability & improves staple crop yield.
- Excess water after supplementary irrigation helped to produce cash crops.
- The environmental water requirement was not compromised with WH intensifications.
- WH intensification modifies river flow regime.
- WH ponds can substantially reduce sediment yield, and improve water quality.

GRAPHICAL ABSTRACT



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ABSTRACT

Water harvesting systems have improved productivity in various regions in sub-Saharan Africa. Similarly, they can help retain water in landscapes, build resilience against droughts and dry spells, and thereby contribute to sustainable agricultural intensification. However, there is no strong empirical evidence that shows the effects of intensification of water harvesting on upstream–downstream social–ecological systems at a landscape scale. In this paper we develop a decision support system (DSS) for locating and sizing water harvesting ponds in a hydrological model, which enables assessments of water harvesting intensification on upstream–downstream ecosystem services in meso-scale watersheds. The DSS was used with the Soil and Water Assessment Tool (SWAT) for a case-study area located in the Lake Tana basin, Ethiopia. We found that supplementary irrigation in combination with nutrient application increased simulated teff (*Eragrostis tef*, staple crop in Ethiopia) production up to three times, compared to the current practice. Moreover, after supplemental irrigation of teff, the excess water was used for dry season onion production of 7.66 t/ha (median). Water harvesting, therefore, can play an important role in increasing local- to regional-scale food security through increased and more stable food production and generation of extra income from the sale of cash crops. The annual total irrigation water consumption was ~4%–30% of the annual water yield from the entire watershed. In general, water harvesting resulted in a reduction in peak flows and an increase in low flows. Water harvesting substantially reduced sediment yield leaving the

* Corresponding author at: Spatial Sciences Laboratory in the Department of Ecosystem Sciences and Management, Texas A&M University, USA.
E-mail address: yihundile@tamu.edu (Y.T. Dile).

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watershed. The beneficiaries of water harvesting ponds may benefit from increases in agricultural production. The downstream social–ecological systems may benefit from reduced food prices, reduced flooding damages, and reduced sediment influxes, as well as enhancements in low flows and water quality. The benefits of water harvesting warrant economic feasibility studies and detailed analyses of its ecological impacts.

1. Introduction

Agriculture in sub-Saharan Africa is largely rainfed. The rainfed agriculture covers 93% of the region's cultivated land (CA, 2007) and is the dominant source of staple food production (Cooper et al., 2008; FAO, 2011; Rosegrant et al., 2002a, 2002b). However, agriculture in sub-Saharan Africa is characterized by low input–output features. Research has shown that there are no agro-hydrological limitations to increasing agricultural production (Rockstrom et al., 2002). The low agricultural production is rather due to sub-optimal management (Licker et al., 2010). Different management techniques have been suggested to improve water productivity and produce "more crop per drop of rain" (Rockstrom et al., 2002). Water harvesting systems are among the technologies that have shown substantial productivity improvements in different regions in sub-Saharan Africa (Barron et al., 2003; Dile et al., 2013b; Fox and Rockstrom, 2003; Oweis and Hachum, 2006). Dile et al. (2013b) conceptually showed that water harvesting systems can build resilience and thereby result in sustainable agricultural intensification.

The water harvesting systems are generally classified into ex situ and in situ water harvesting systems (Dile et al., 2013b). *Ex situ* water harvesting systems collect water from a large area and have a drainage catchment, conveyance structures, and storage structures (Dile et al., 2013b; Oweis and Hachum, 2006; Rosegrant et al., 2002a). *In situ* water harvesting systems capture and store the rainfall where it falls. The ex situ and *in situ* water harvesting systems are described in various publications (Biazin et al., 2012; Dile et al., 2013b; Ngigi, 2003; Oweis and Hachum, 2006; Vohland and Barry, 2009).

Despite the promising benefits of water harvesting, there are concerns that intensification of water harvesting systems may cause negative externalities on the downstream social–ecological systems by reducing streamflows. Studies in the last decade or so have produced two schools of thought (Dile et al., 2013b). The first suggests that intensification of water harvesting upstream may reduce streamflows and thereby negatively affect downstream social–ecological systems (Batchelor et al., 1999; Garg et al., 2012; Glendenning and Vervoort, 2011). The other school of thought suggests that streamflows are not substantially reduced with intensification of water harvesting systems, and they have negligible negative externalities on the environment (Andersson et al., 2011, 2013; De Winnaar and Jewitt, 2010; Schreider et al., 2002). The variation in the findings could be due to differences in the biophysical environments (e.g., land use, soil type, climate, topography and catchment size), the scale of water harvesting intensification, and the types of water harvesting systems implemented. Furthermore, most of previous studies represented several small-scale water harvesting interventions as a single lumped water harvesting structure, which is a misrepresentation of the hydrological dynamics in the landscape and also have paid little attention to the spatial location of water harvesting systems in the landscape.

Water management interventions (e.g., water harvesting systems) are required at meso-scale watershed level (a catchment area of 10–1000 km^2) to provide maximum benefits and to capitalize the untapped potential of rainfed agriculture for small-scale farmers (CA, 2007).

Uhlenbrook et al. (2004) also recommend that meso-scale watershed development is essential for optimal management and protection of water resources. Likewise, Tilman et al. (2002) suggest that landscape-scale management at meso-scale holds significant potential for reducing off-site consequences of agriculture.

Therefore, the goal of this study is to develop a decision support system in a meso-scale watershed within Lake Tana basin to help determine suitable areas for locating *ex-situ* water harvesting systems and the corresponding sizes of the water harvesting ponds. Also, we investigate the holistic implications of intensification of *ex situ* water harvesting systems on upstream–downstream ecosystem services in terms of crop yields, water productivity, environmental flow requirements, and sediment yield.

2. Method and material

2.1. Study area

The study area is a meso-scale watershed located in Megech watershed, North Gondor administrative zone within Lake Tana basin of the Upper Blue Nile basin, Ethiopia (Fig. 1). The study watershed has a catchment area of 10 km^2. The topography is rugged, with an elevation between 1888 and 2144 m above sea level. The climate in the study area is dominated by tropical highland monsoon with most of the rainfall (70–90%) occurring between June and September (Mohamed et al., 2005).

A large part of the population in the study watershed bases their livelihood on agricultural production (CSA, 2007). Much of the agricultural practice in the study watershed is small-scale, rainfed agriculture (Awulachew et al., 2010). The inter- and intra-annual rainfall variability in the study watershed is high (Bewket and Conway, 2007; Seleshi and Camberlin, 2005), and the subsistence rainfed agriculture is extremely vulnerable to this rainfall variability (World Bank, 2006). Therefore, upgrading rainfed agriculture, for example, through investment in water harvesting, should be among the strategies to increase resilience against climate related shocks and improve the livelihood of farmers in the watershed (Awulachew et al., 2005).

2.2. Data inputs and modeling setup

The Soil and Water Assessment Tool (SWAT) was used in this study to develop a decision support system to investigate implications of intensifying water harvesting on the upstream–downstream ecosystem services. ArcSWAT-2012 (rev: 591) (Neitsch et al., 2012; Winchell et al., 2013) for ArcGIS 10.0 was used to set up the SWAT model. SWAT is a physically based model, developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in watersheds with varying soil, land use, and management conditions (Neitsch et al., 2012). The SWAT model has the capability to simulate the hydrological cycle, vegetation growth, and nutrient cycling with a daily time step by disaggregating a river basin into sub-basins and Hydrologic Response Units (HRUs). HRUs are lumped land areas within sub-basins that are comprised of unique land cover, soil and management combinations. The use of HRUs allows the model to reflect differences in evapotranspiration and other hydrologic conditions for different land covers and soils (Neitsch et al., 2012). SWAT has been applied with satisfactory results in many watersheds across the world (Gassman et al., 2007), including highlands of Ethiopia (Ayana et al., 2015; Baker et al., 2015; Betrie et al., 2011; Dile et al., 2013a; Easton et al., 2010; Fuka et al., 2013; Schmidt and Zemadim, 2015; Setegn et al., 2010b; Yesuf et al., 2015).

The spatial data used in SWAT included a digital elevation model (DEM), stream network, soil, and land cover. The DEM was used to