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

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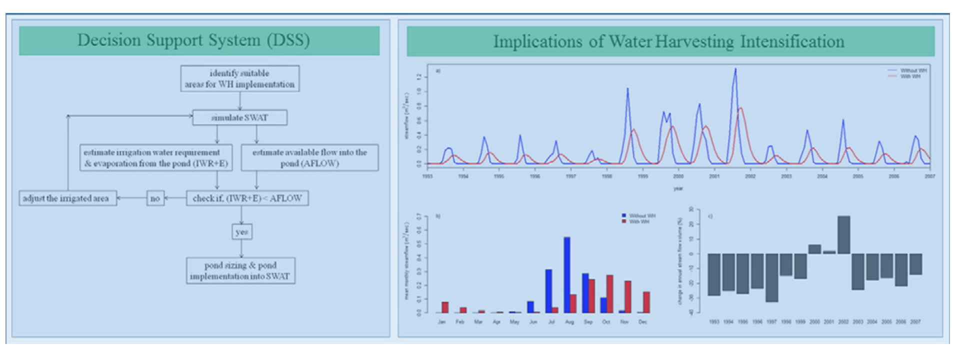
HIGHLIGHTS

- 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

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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

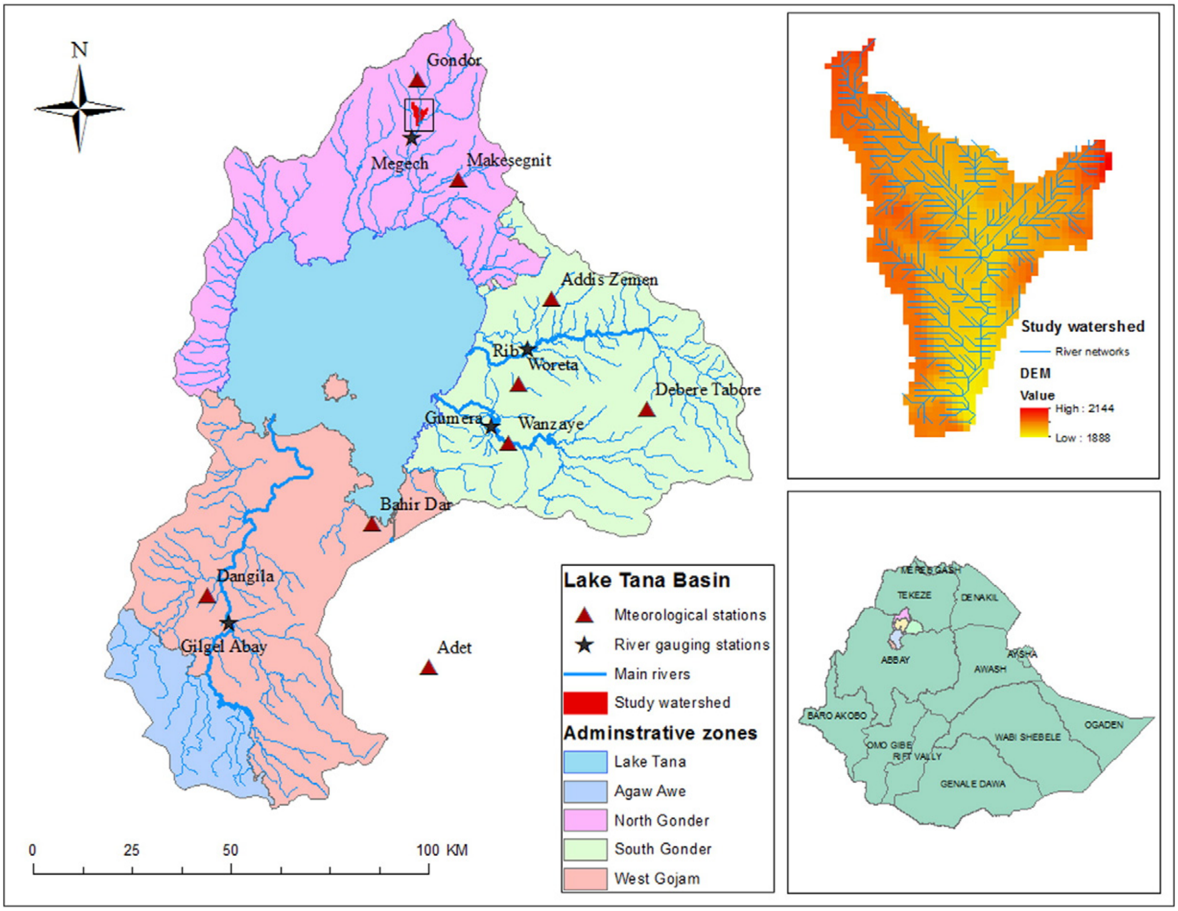

Fig. 1. Location of the studied meso-scale watershed in the Lake Tana basin and in the Ethiopian River Basin system (lower box to the right). The studied watershed is marked with a black box in the Lake Tana basin — enlarged and displayed in the upper right corner. The Ethiopian River Basin system is presented in the lower right corner. The Lake Tana basin is shared by four administrative zones, and four major rivers drain into the lake.

delineate the sub-basins in the ArcSWAT interface, and the stream network dataset was superimposed onto the DEM to define the location of the streams. Data-sets on land use and soil data were important for defining the HRUs. The DEM data was obtained from the CGIAR Consortium for Spatial Information website (CGIAR-CSI, 2009), and have a resolution of 90 m by 90 m. The stream network, land cover, and soil maps of the study area were collected from the Ethiopian Ministry of Water Resources (MoWR, 2009). The soils' physical and chemical properties parameters that are required by SWAT were derived from the digital soil map of the world CD-ROM Africa map sheet (FAO, 1995).

Weather data plays a major role in simulating the hydrological processes in SWAT. The weather data required to set up the SWAT model consisted of daily rainfall and maximum and minimum temperature. The weather data was collected from the Ethiopian National Meteorological Services Agency (ENMSA, 2012). Weather data (1990 to 2011) from a weather station closest to the meso-scale watershed was used and any missing data (which accounts for 5.2% of the total observation) was computed using SWAT's built-in weather generator (Neitsch et al., 2012). The annual rainfall amounts in the watershed ranged from 978 mm to 1850 mm. The highest and lowest amounts were observed in 1995 and 2001, respectively, which were used to represent a typical wet and dry year, respectively, in the analysis. The annual rainfall data that was used for the analysis is presented in the Supplementary Information (SI) Fig. S1.

2.3. Model calibration and validation

2.3.1. Calibration strategy

Calibration and validation are fundamental processes used to demonstrate whether models can produce suitable results in a particular application. During calibration and validation, model simulated data were compared with observed data by optimizing parameters in an effort to simulate real-world conditions and reduce model prediction uncertainty (Daggupati et al., 2015b). Since there was no observed data to calibrate the model at the meso-scale watershed, the model parameters were initially optimized using the observed data at the outlet of the Megech river watershed (Fig. 1). A separate SWAT model was developed for the Megech river watershed and was calibrated and validated. After satisfactory results, the parameters were transferred into the meso-scale catchment which is inside the Megech watershed. Several studies (Cho et al., 2013; Daggupati et al., 2015a; Pagliero et al., 2014; Parajka et al., 2005) have focused on transferring parameters from gauged to ungauged watersheds and have found that the best results were seen when the parameters are transferred within similar hydrological and geophysical regions. Daggupati et al. (2015a) have calibrated the SWAT model for West Lake Erie basin in the USA using outlet data and verified at various locations within the watershed. They found that the model produced reasonable results at various locations since the watershed was fairly homogeneous. Since the meso-scale watershed is within the Megech watershed and has similar hydrogeological conditions, transferring parameters can be justified.

2.3.2. Calibration of Megech watershed

The model setup for the Megech watershed and the Lake Tana basin is presented in Dile and Srinivasan (2014). The streamflow data used for model calibration and validation at the Megech river gauging station were for the 1990–2007 period and were obtained from the Ethiopian Ministry of Water and Energy (MoWE, 2012). Thus, the evaluation of the model simulation was limited to the 1990–2007 period, even though the climate data spans a longer time period. The Angereb reservoir is located in the Megech watershed and was included in the management data, and the average monthly reservoir outflow was obtained from the Gondor municipality water supply authority (GWSA, 2012). The volumes of the Angereb reservoir at the principal and emergency spillways are 3.53 Mm^3 and 5.16 Mm^3, respectively (Dile and Srinivasan, 2014).

Calibration and uncertainty analysis of the hydrological parameters was performed using the Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm (Abbaspour et al., 2004, 2007). SUFI-2 accounts for all sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters and measured data as parameter uncertainty (Abbaspour et al., 2004, 2007; Schuol et al., 2008). The degree of the uncertainties are quantified by measures called p-factor and r-factor. The p-factor is the percentage of measured data bracketed by the 95% prediction uncertainty (95PPU). The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin-hypercube sampling. The r-factor is the average thickness of the 95PPU band divided by the standard deviation of the measured data. A p-factor close to 1 and an r-factor close to zero represents strong model performance.

The calibration and uncertainty analysis were performed using observed streamflow at the Megech river gauging station. The calibration period ranges from 1993–1999, and the validation period ranges from 2002–2007. The Angereb reservoir was filled during 2000–2001, and these years were excluded from the calibration and validation period as the reservoir filling operation was not known accurately. Dile and Srinivasan (2014) validated the crop yield simulation against observed crop production and found that the model performed well in predicting crop growth in the Megech watershed.

The performance of the model was evaluated using Nash-Sutcliffe Efficiency (NSE) and Percent bias (PBIAS). Nash-Sutcliffe Efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). NSE can range from $-\infty$ to 1. An NSE value of 1 corresponds to a perfect match between observed and simulated streamflow. An NSE value between 0 and 1 is considered an acceptable level of performance, whereas an NSE value ≤ 0 suggests that the observed mean is a better predictor than the model. Percent bias (PBIAS) compares the average tendency of the simulated data to the corresponding observed data (Gupta et al., 1999). The optimal value of PBIAS is 0, while positive values indicate model underestimation and negative values indicate model overestimation (Gupta et al., 1999). Moriasi et al. (2007) suggested that PBIAS can easily quantify water balance errors and indicate model performance.

Sediment yield data were not available, and calibration of sediment-related parameters was not performed. Rather, the parameters calibrated by Setegn et al. (2009) for Anjeni watershed were adopted. The Anjeni watershed is located in the Upper Blue Nile basin close to the Lake Tana basin. Setegn et al. (2009) applied these parameters to investigate the vulnerability of the Lake Tana basin for erosion. They justified that the Anjeni watershed has similar biophysical conditions as the Lake Tana basin since they found similar flow and sediment characteristics between the two watersheds. They later published these findings independently for the Anjeni watershed (Setegn et al., 2010a). Setegn et al. (2009, 2010a) found parameters similar to those found by Betrie et al. (2011) for the entire Upper Blue Nile Basin.

The calibrated model parameters of both hydrology and sediment from the Megech river watershed were used in the meso-scale watershed simulation for studying the implications of water harvesting implementation (Table 1). For a detailed description of the parameter names, refer to Arnold et al. (2012).

2.4. A decision support system for determining the location and size of water harvesting ponds

We proposed a decision support system which can be applied in any location that identifies suitable areas for water harvesting implementation, assesses irrigation water requirement, and designs appropriately sized water harvesting ponds for each parcel of suitable land. The process for determining the location and size of water harvesting ponds in SWAT first identifies suitable areas for water harvesting and then determines pond size. We thereby assessed the holistic implications of water harvesting systems on the upstream–downstream ecosystem services. The decision support system is presented below and is also depicted in Fig. 2.

2.4.1. Identifying suitable areas for water harvesting

The meso-scale watershed in the present study has an area of ~10 km^2, which was subdivided by ArcSWAT into sub-basins between ~1 and 6 ha (Fig. 1). These sub-basin sizes were of the same order of

Table 1
Calibrated SWAT parameters, their descriptions and fitted values (Arnold et al., 2012). Sediment related parameters are adapted from Setegn et al. (2010b). The units for the parameters are also provided. Parameters where units are not provided are unitless.

Variable	Parameter name	Descriptions	Fitted parameter value
Flow	r_CN2[a]	Curve number	−0.0958
	v_ALPHA_BF[b]	Base-flow alpha factor (days)	0.9330
	a_GW_DELAY[c]	Groundwater delay time (days)	−4.95
	a_GWQMN	Threshold water depth in the shallow aquifer required for return flow to occur (mm)	223.00
	a_GW_REVAP	Groundwater "revap" coefficient	0.15094
	v_ESCO	Soil evaporation compensation factor	0.4236
	v_CH_K2	Channel effective hydraulic conductivity (mm/h)	12.54
	r_SOL_AWC	Available water capacity of the soil (mm)	0.0506
	a_REVAPMN	Threshold water depth in the shallow aquifer for "revap" to the deep aquifer to occur (mm)	169.50
Sediment	v_SPCON	Linear re-entrainment parameter for channel sediment routing	0.005
	v_Ch_COV	Channel cover factor	0.35
	v_Ch_ERODMO	Channel erodibility factor	0.5
	v_USLE_P	USLE equation support practice factor	0.8
	v_SPEXP	Exponent parameter for re-entrainment in channel sediment routing	1.39
	v_USLE_C	USLE Land cover factor	0.27

[a] The qualifier (r_) refers that the original parameter value is multiplied by (1 + fitted parameter value).
[b] The qualifier (v_) refers that the original parameter value is to be replaced by the fitted parameter value.
[c] The qualifier (a_) refers that the fitted parameter value is added to the original parameter value.

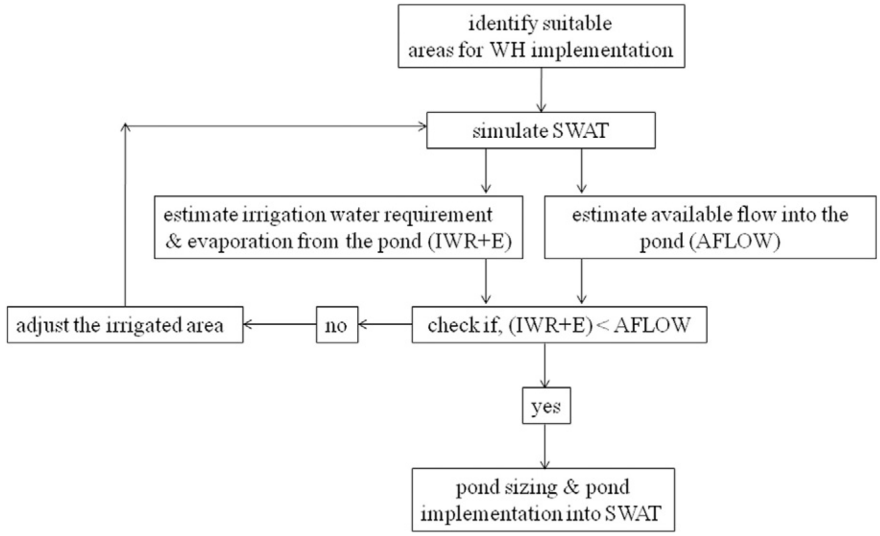

Fig. 2. A Decision Support System (DSS) to determine the volume of water harvesting ponds for suitable areas for water harvesting.

magnitude as the sizes of land owned by households in the Lake Tana Basin. The watershed was delineated to this level of detail in order to implement water harvesting ponds in every suitable parcel of land owned by a household (<2 ha, Jayne et al., 2003), and thereby was able to quantify the implications of intensifying water harvesting systems. Suitable areas were defined as those having a slope < 8%, with soils classified either as luvisols or vertisols, and where the predominant land use is agriculture. Slope of less than 8% was chosen in this study because of its suitability for water harvesting structures (Critchley and Siegert, 1991; Mati et al., 2006). Vertisols and luvisols soils were selected because Araya et al. (2010) and Tulema et al. (2005) reported that vertisol is the major soil type used to cultivate teff, and luvisols are characterized by the presence of mixed mineralogy, high nutrient content, and good drainage, making them suitable for a wide range of agricultural practices. Agricultural lands were considered since the aim of this study was to evaluate the effects of upgrading rainfed agriculture on existing cultivated land. Furthermore, we adopted the principle of avoiding the conversion of other land use types into agricultural land, based on the assessment that the few remaining ecosystem services from non-cultivated lands need to be preserved.

2.4.2. Pond size determination

Pond size is determined based on the amount of water needed to meet irrigation water requirements for all seasons (including double cropping) for each suitable HRU. Irrigation was applied from the water harvesting ponds whenever the crop experienced at least 25% crop water stress. The volumetric crop water requirement for each suitable HRU within a sub-basin was calculated to determine the amount of water required to meet the crop water requirements under extreme dry conditions on the record. The preliminary pond size that could capture the maximum volume of irrigation water was identified (IWR). The sum of evaporation (E) from the preliminary pond and the irrigation water requirement (IWR) was considered to be the actual volume of the water harvesting pond (IWR + E). This volume was then compared with the annual available flow (AFLOW) into the pond during the 1993–2007 time period. In cases where the irrigation water requirement and evaporation from the pond (IWR + E) were more than the annual available flow into the pond (AFLOW), the irrigated areas with water harvesting were reduced iteratively until the irrigation water requirement and evaporation from the pond was equal to or less than the annual available flow into the pond (Fig. 2). Therefore, in each suitable HRU, the maximum volume of water to meet crop water requirement and evaporation from the pond make up the pond volume.

In the present study, irrigation water demand was determined based on the amount of water required to meet supplementary irrigation for a cereal crop (teff) during the rainy season and a fully irrigated cash crop (onion) during the dry season. The pond size that could fulfill the crop water requirement for teff and onion under any climatic and nutrient application condition was implemented in SWAT.

2.5. Modeling the meso-scale watershed employing water harvesting structures

Assumptions concerning agricultural management operations were based on existing farmers' practices in the region. A number of irrigation and nutrient management scenarios were designed based on available information in the literature and our field research experience. They were analyzed focusing on several variables such as crop yields, water productivity, and downstream water availability.

2.5.1. Crop rotation and other management operations

Farmers in the Lake Tana basin are interested in using water harvesting ponds for cultivating vegetable crops during the dry season. However, because of rainfall variability and limited nutrient application, agricultural production is low and highly variable, even in the rainy season. Therefore, water harvesting in this study was tested for farmers' capacity to bridge dry spells during the rainy season as well as for irrigating cash crops during the dry season.

Teff is the most common rainfed crop in the study area. Yihun et al. (2013) showed that teff is very sensitive to water stress, especially during the flowering stage. Thus, in this study, supplementary irrigation from the water harvesting ponds was applied when the crop experienced water stress. The agricultural management operations for teff in the meso-scale watershed were similar to the case in the Megech watershed (Dile and Srinivasan, 2014). During the dry season, in areas that are close to rivers, farmers cultivate onion using the river water. Moges et al. (2011) studied water balance simulations and economic analysis of different *ex-situ* water harvesting systems for growing onion in Ethiopia. They found that the economics of onion production using water harvesting systems is feasible. Therefore, the excess water after supplementary irrigation for teff was used for cultivating onion during the dry season. The onion was planted on January 5th and harvested on April 11th. Fertilizer was applied in two splits; the first split during planting, and side dress applied after six weeks. The maresha plow system used in teff crops was implemented (Temesgen et al., 2008). Irrigation was applied only if water was available in the water harvesting ponds.

2.5.2. Nutrient scenarios

The blanket fertilizer recommendation for teff in most parts of Ethiopia is 100 kg/ha DAP and 100 kg/ha urea (EIAR, 2007). EIAR (2007) recommends a single application of DAP fertilizer and two split applications of urea (50 kg/ha applied at planting and the remaining 50 kg/ha applied 30 to 35 days after planting). Likewise, EIAR (2007) recommends 150 kg/ha urea and 200 kg/ha DAP for onion production. However, Dile and Srinivasan (2014) showed that the current nutrient application practices of farmers are far lower than the recommendation from EIAR (2007).

Various studies (Barron and Okwach, 2005; Oweis and Hachum, 2006) have shown that water harvesting combined with better nutrient application can substantially increase crop yield. Therefore, we studied the effect of water harvesting with a baseline nutrient application (farmers' current practice) and two modified blanket nutrient recommendation scenarios for teff, and a single modified blanket nutrient recommendation for onion. The nutrient application scenarios are presented in Table 2. The basis for the nutrient scenario decisions were provided in the SI.

2.5.3. Evaluating water harvesting implications

The biophysical systems before and after water harvesting and various nutrient scenario implementations were analyzed in order to understand their effects on the upstream–downstream ecosystem services. The analyses included crop yields, water productivities, environmental flow requirements, and sediment yield.

2.5.3.1. Crop yields. The differences in crop yield among water harvesting and nutrient application scenarios and the baseline scenario were estimated as percentage changes, as:

$$\%\text{change} = \left(\frac{\text{scenario}-\text{baseline}}{\text{baseline}}\right) * 100. \quad (1)$$

The significance of the difference between two scenarios was calculated with the Wilcoxon rank sum test (Hollander and Wolfe, 1999). The analysis was performed using the R statistical computing environment (R Development Core Team, 2015).

2.5.3.2. Water productivity. The crop water productivities (CWP) were calculated as the ratio of grain yields to actual evapotranspiration.

$$\text{CWP} = \frac{\text{Y}}{\text{ET}_\text{a}} \quad (2)$$

CWP is crop water productivity (kg/m^3), Y is grain yield (kg/ha), and ET$_a$ is actual evapotranspiration (m^3/ha) during the crop growth period (July 22–December 5). The water productivities (WP) were estimated for the baseline situation and after water harvesting and nutrient scenario implementations for all HRUs and seasons (1993–2007).

Table 2
Nutrient scenarios.

Scenario	Crop	Timing	DAP (kg/ha)	Urea (kg/ha)
Baseline nutrient application	Teff	Planting	30	15
		Side dress		15
	Onion	Planting	30	85
		Side dress		85
Blanket nutrient recommendation (BNR1)	Teff	Planting	30	50
		Side dress		50
	Onion	Planting	30	85
		Side dress		85
Blanket nutrient recommendation (BNR2)	Teff	Planting	30	85
		Side dress		85
	Onion	Planting	30	85
		Side dress		85

2.5.3.3. Environmental water requirement accounting. Environmental flows are defined as the “quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems” (Brisbane Declaration, 2007). However, the allocation of environmental flows and how to balance this with other water demands is a difficult task (Pahl-Wostl et al., 2013). Environmental water requirements vary depending on the objective of environmental water management (Smakhtin et al., 2004). The objective must be to aim to sustain the desired future ecosystem state together with the bundle of services these ecosystems supply for human benefit (Pahl-Wostl et al., 2013; Smakhtin et al., 2004). Pahl-Wostl et al. (2013) suggested that rules must exist to determine environmental flow requirements which in their turn are coordinated with other types of basin-wide water and land uses and management practices.

There are different methods of calculating the environmental flow requirement. The environmental flow accounting methodology suggested by Smakhtin et al. (2004) was used in this study. The objective in this study is not to carry out a dynamic environmental water requirement analysis but rather to define a water threshold below which water related ecological functions risk being undermined, as a reference point when assessing downstream implications of intensified water harvesting upstream. Therefore, the approach suggested by Smakhtin et al. (2004) was appropriate to the scope of this study.

Smakhtin et al. (2004) prescribed four conservation status/management objectives; the corresponding descriptions of ecological status and hydrological requirement are presented in the SI, Table S1. Each acceptable conservation status is associated with two hydrological indices, a low flow requirement and a high flow requirement. We calculated environmental flow requirements to maintain a “good” ecological status in the river system, which is defined as largely sustaining biodiversity and aquatic habitats while developing water resources, and requires allocating 65–80% of total annual baseflow to ecosystems (or discharge exceeded 9 out of 12 months) and ensuring that Q75 is always exceeded (Smakhtin et al., 2004). The total annual environmental water requirement is, therefore, calculated as a sum of the low flow requirement and high flow requirement estimates (Smakhtin et al., 2004). The environmental flow requirement was estimated at the outlet of the watershed. A summary of the environmental flow requirement accounting by Smakhtin et al. (2004) is presented in the SI.

2.5.3.4. Sediment yield. Various scholars have cautioned that severe soil erosion in Ethiopia is degrading the natural resource base for the agricultural sector (Hurni et al., 2005; Taddese, 2001). Moreover, the siltation problem is threatening natural lakes and man-made reservoirs (Haregeweyn et al., 2006; Tamene et al., 2006). Different measures have been suggested to mitigate soil erosion in Ethiopian highlands (Betrie et al., 2011; Descheemaeker et al., 2006; Gebremichael et al., 2005; Herweg and Ludi, 1999). It is evident that the introduction of water harvesting ponds can trap sediment leaving the sub-basins. The change in sediment yield before and after water harvesting implementation was assessed at the outlet of the watershed.

3. Results

3.1. Model calibration and validation

Calibration of the model at the Megech gauging station resulted in an NSE value of 0.76 and a PBIAS of 4%, which indicates that the model capably reproduced what was observed in the field (Moriasi et al., 2007). As seen from Fig. 3a, there was generally good agreement between the simulated and the observed streamflows, except for a minor mismatch in the peaks. The values of NSE and PBIAS for the validation period were 0.74 and 40%, respectively. The NSE value suggested that the model performed well; however, the PBIAS value indicated that the model performance was unsatisfactory. Fig. 3b shows that the

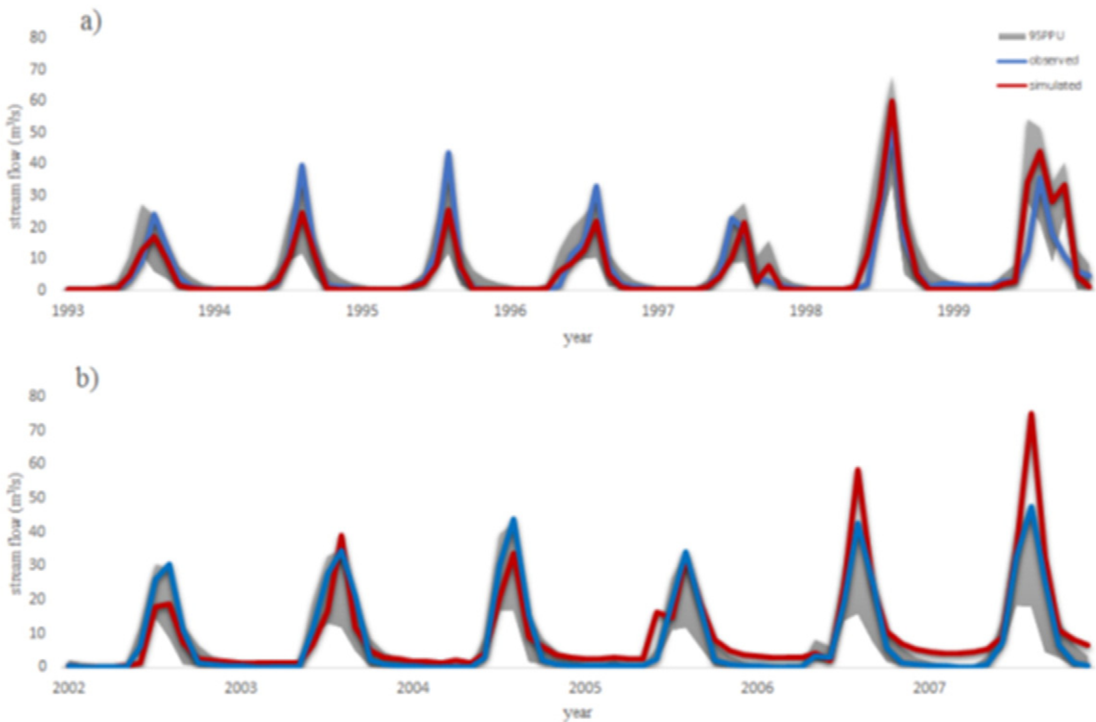

Fig. 3. Simulated vs observed monthly stream flow and the 95% predication uncertainty (95 PPU) at Megech watershed in the Lake Tana Basin. a) Calibration period, and b) validation period.

simulated streamflows were consistently underestimated compared to measured values, in particular during 2006 and 2007. The unsatisfactory performance during validation years may be related to the operation of Angereb reservoir. For example, the data for water withdrawal for Gondor town water supply may be more than the actual withdrawal. However, our model calibration and validation results at the Megech river gauging station were better than the results reported by Setegn et al. (2010b). Their NSE values for calibration and validation are 0.18 and 0.04, respectively. Setegn et al. (2010b) also reported that the poor model performance at the Megech river may be related to upstream dam construction or diversion of streams for small-scale irrigation and other unknown activities in the sub-basins.

The observed flow is bracketed within the 95PPU most of the time except at a few peak periods during the calibration period (Fig. 3a). The p-factor was 0.8, which suggests that 80% of the measured monthly streamflow values could be bracketed by the 95PPU. The r-factor was 0.65 (out of perfect 0, but reasonable at around 1; Schuol et al., 2008). During the validation period, 46% of the monthly streamflow values were bracketed by the 95PPU and the r-factor was 0.53, which signifies a narrow 95PPU band. The lower p-factor during validation period is mainly due to 95PPU not capturing the observed streamflows during low flows (Fig. 3b) and can be attributed to the Angereb reservoir operation uncertainties as discussed earlier. Overall, results suggest that the predictions in this study are within reasonable limits of uncertainty.

3.2. Suitable area for water harvesting, and pond dimension

The total area that was classified as suitable for water harvesting implementation was 3.79 km^2, corresponding to 38% of the total watershed area. Applying the DSS resulted in 257 ponds implemented in the watershed. The volume of the ponds in each sub-basin ranged between 1,170 m^3 and 8,750 m^3. Around 40% of the water harvesting ponds had a volume less than 1,500 m^3, and 36% of the ponds had a volume between 1,500–3,000 m^3. The ponds that had a volume range between 6,000–9,000 m^3 account for less than 1%, i.e., two water harvesting ponds. The frequency diagram for the volume of water harvesting ponds implemented in the watershed is presented in SI, Fig. S2. The areas irrigated from each pond ranged between 0.85 ha and 5.1 ha.

In the case of the studied watershed, and on an annual basis, there were sufficient runoff flows into ponds to meet the irrigation water requirements and evaporation from ponds for all areas that are suitable for water harvesting. However, within the year and because the ponds were constantly filling or emptying, there were periods when some ponds ran out of water in the midst of the crop growth period.

Most of the water harvesting ponds implemented in the watershed had a volume of less than 1,500 m^3. These ponds were sufficient to store water for irrigating a cultivated land of 0.85 ha for double cropping. The average land holding in Ethiopia is less than 2 ha (Jayne et al., 2003), and thus such types of ponds are sufficient to store water that could meet the water requirements to bridge rainfall variability during wet seasons and produce a second cash crop for a household during dry seasons. The other dominant pond dimension has a volume of 1,500–3,000 m^3. These types of ponds can be built jointly by two or more farmers who have cultivated lands next to each other. The larger ponds of volumes more than 3,000 m^3 can be built as village or community ponds and owned and used by several households.

3.3. Impacts of intensification of water harvesting

3.3.1. Crop yield

Supplementary irrigation from water harvesting ponds and improved nutrient applications increased crop yield significantly (p-value: $<2.2*10^{-16}$). There was large variability in crop yields across HRUs and seasons (Fig. 4). For example, in some climatic years and in irrigated HRUs, the teff yield reached up to ~6 t/ha. The highest yields were observed during optimal conditions where there were sufficient water and nutrients. Supplementary irrigation with the baseline nutrient application increased the spatio-temporal median (across all HRUs and seasons) teff yield by 57% (Table 3). The teff yield during the baseline condition was 0.7 t/ha. However, implementation of supplementary irrigation with the baseline nutrient application increased the crop yield

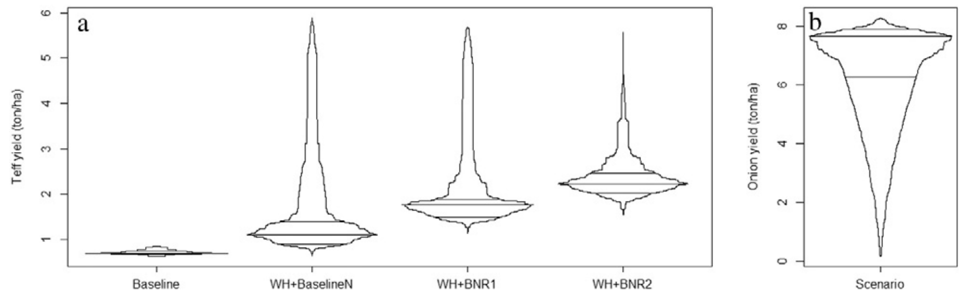

Fig. 4. Box-percentile plot summarizing the a) teff and b) onion production across all irrigated HRUs and seasons (1993–2007). For teff, it presents the yield with baseline conditions, and supplementary irrigation with three nutrient scenarios (refer Table 2 for the different scenarios). While for onion, irrigation and a single nutrient application was considered. The median, 25th and 75th percentiles are marked with line segments across the box. The width of the box at any height up to the 50th percentile is proportional to the percentile of that height, and the width above the 50th percentile is proportional to 100 minus the percentile.

to 1.1 t/ha. Increasing the baseline nutrient application to the recommended nutrient application scenario significantly increased the teff yield (p-value: $<2.2^*10^{-16}$). Full-scale application of blanket nutrient recommendations (BNR2) increased the spatio-temporal median teff yield by 217% (2.23 t/ha), a threefold increase (p-value: $<2.2^*10^{-16}$). In the best combination of biophysical and climatic conditions, the increase in yield reached 675% (97.5th percentile) (Table 3). The results of this study were consistent with other field studies in Ethiopia. For example, Araya et al. (2010), applying 60 kg/ha N and 46 kg/ha P, showed an increase of 205% to 280% teff yield between no irrigation and optimal irrigation treatments in the Mekelle area of Northern Ethiopia. Supplementary irrigation with baseline nutrient application, BNR1 and BNR2 scenarios on average added an additional teff production of 177 t/year, 313 t/year, and 428 t/year, respectively, to the food supply system of the watershed.

Moreover, the excess water stored in the water harvesting ponds was used for dry season irrigation to produce onion. The median spatio-temporal onion yield was 7.66 t/ha. In some HRUs and seasons, onion production reached up to 8.22 t/ha (97.5th percentile). However, in other seasons and HRUs the onion production was as low as 1.33 t/ha (2.5th percentile). Similar onion yields were seen during field trials with irrigation and fertilization in Ethiopia (Kifle et al., 2007; Bekele and Tilahun, 2007). The total onion production in the watershed increased to ~1,760 t/year as a result of irrigation from water harvesting.

In a typical dry year (e.g., 1995), with supplementary irrigation and the baseline nutrient scenario, the median increase in teff yield was 63%. Increasing nutrient application with supplementary irrigation improved teff production further. With supplementary irrigation, the median increase in teff yield was 146% and 241% for the BNR1 and BNR2 scenarios, respectively. The percentages of change in teff yield for a typical dry year with supplementary irrigation and three nutrient scenarios across the watershed are provided in Fig. 5a, b and c. Onion production in the watershed during a typical dry year ranged from 0.17–8.3 t/ha (median 8 t/ha) (Fig. 5d).

In a typical wet year (e.g., 2001), the increase in median teff yield with supplementary irrigation and baseline nutrient application was 37%. Supplementary irrigation and nutrient scenarios BNR1 and BNR2 provided greater yields. The median increase in teff yields with supplementary irrigation and BNR1 and BNR2 scenarios was 120% and 229%, respectively. The percentage changes in teff yields for a typical wet year with supplementary irrigation and three nutrient scenarios across the watershed are provided in Fig. 6a, b and c. Onion production during a typical wet year ranged between 1.2 and 8.1 t/ha (median of 7.9 t/ha) (Fig. 6d).

This study shows that the improvements in teff yields due to supplementary irrigation were higher during dry climatic years compared to wetter years. However, onion production was higher during wet climatic years since there was more water stored in the water harvesting ponds for dry season irrigation. This, therefore, suggests that water harvesting is important in any climatic environment to boost production in dry climatic years, and/or to produce more cash crops in wet climatic years.

Table 3
Percentage changes in teff yields for different scenarios in relation to the baseline condition. Values for the median, 2.5th and 97.5th percentile indicate the distribution of change across all HRUs and seasons (1993–2007).

Scenarios	Percent change in teff yield		
	2.5th percentile	Median	97.5th percentile
WH + baseline nutrient[a]	15 (0.79)[b]	57 (1.11)	667 (5.26)
WH + BNR1	95 (1.34)	134 (1.77)	675 (5.32)
WH + BNR2	149 (1.83)	217 (2.23)	364 (3.65)

[a] WH refers water harvesting.
[b] Values in parenthesis are teff yield (t/ha).

3.3.2. Evapotranspiration and water productivity

Evapotranspiration increased with supplementary irrigation (Table 4). The highest increase (50 mm) was for HRUs and seasons where the available water to meet crop evapotranspiration in the baseline condition was the lowest (2.5th percentile). The contribution of supplementary irrigation during periods where there was sufficient water for evapotranspiration (97.5th percentile) was small — the increase in evapotranspiration between the baseline condition, and the supplementary irrigation and baseline nutrient application scenario was merely 9 mm. There was a modest additional increase in evapotranspiration as nutrient application increased (Fig. 7). For example, the increase in evapotranspiration as the nutrient application increased from the baseline nutrient application and supplementary irrigation to BNR1 and BNR2 nutrient applications and supplementary irrigation was 19 mm and 25 mm (2.5th percentile), respectively.

Supplementary irrigation resulted in an increase in water productivity (Fig. 7). The median spatio-temporal water productivity with the baseline condition was less than 0.2 kg/m^3; however, it was improved to 0.45 kg/m^3 with water harvesting implementation and better nutrient application conditions (Table 4). In HRUs with convenient biophysical situations (97.5th percentile), water harvesting and improved nutrient application provided a water productivity of about 1.1 kg/m^3.

3.3.3. Downstream water availability and environmental flow requirements

The total annual amount of water used for irrigation over the whole watershed was small compared to the total annual water yield generated from the watershed (Fig. 8). Annual irrigation water consumption was between 4%–30% of the total water yield from the watershed in the same year. The maximum irrigation application in relation to the total water yield from the watershed was observed in a relatively dry year (1995) where a larger amount of supplementary irrigation for teff crops was needed. Analogously, the smallest irrigation application compared to the total water yield from the watershed was observed in 2001, which was the wettest year on record. In the wettest years in

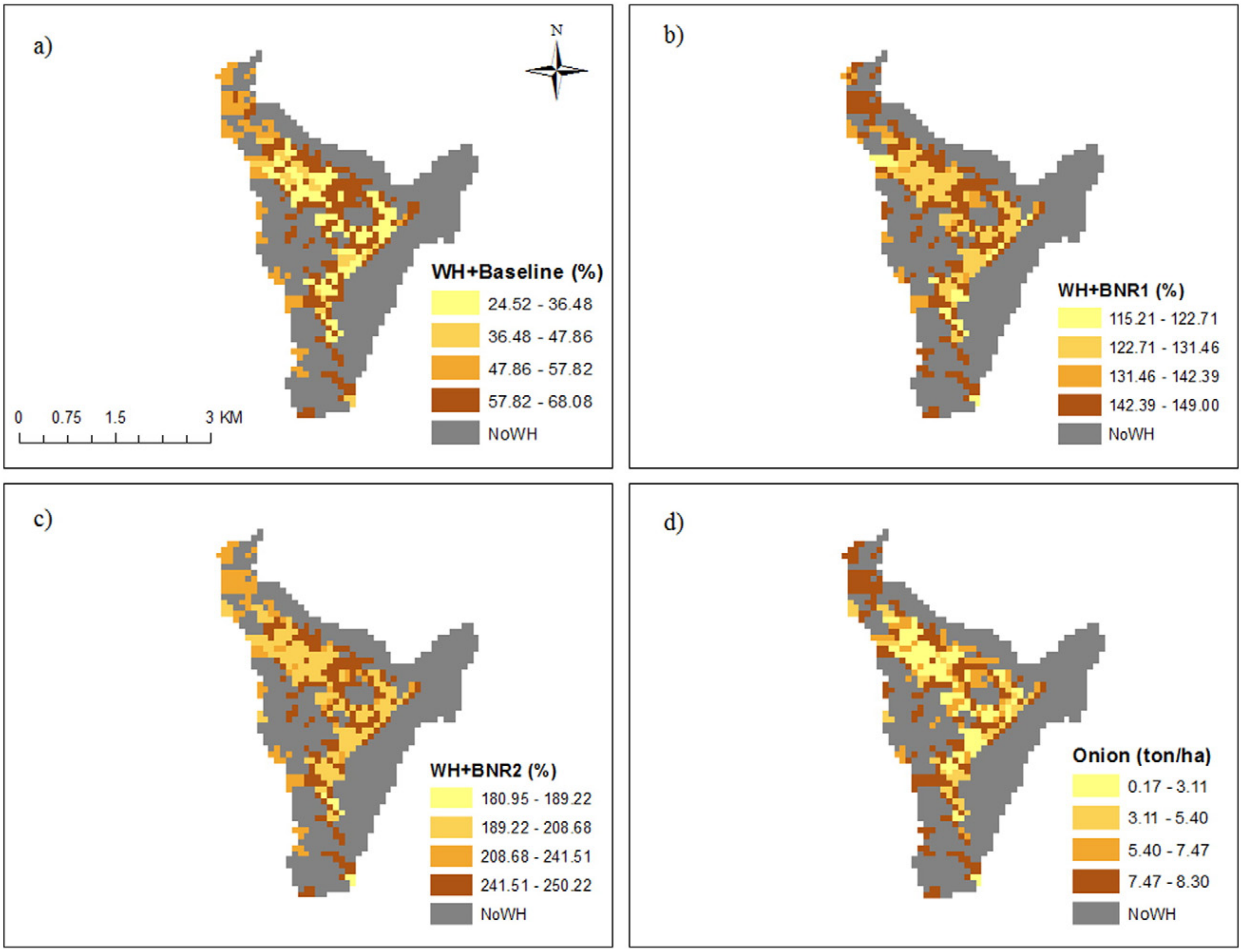

Fig. 5. Crop production with water harvesting and nutrient scenarios in typical dry year (e.g. 1995). Percent change in teff yield with supplementary irrigation and a) baseline nutrient application, b) BNR1, and c) BNR2 scenarios, compared to baseline condition teff production; and d) onion production (t/ha) with irrigation and single case nutrient application. WH refers Water Harvesting, and refer Table 2 for the different scenarios.

the record, the demand for supplementary irrigation for teff was very small, and much of the irrigation consumption was for growing onion during the dry seasons.

The streamflow in the studied watershed was highly variable with ~84% of the annual flow occurring in just three months (July–September), and ~98% of the flow occurring in five months (June–October). The annual flow volume corresponding to a low flow requirement (to maintain "good" management objectives) was found to be 19,900 m^3. The high flow volume requirement was 729,000 m^3. Thus, the total annual environmental water requirement was 748,900 m^3, representing 8.2% to 61% of the annual runoff volume, depending on the climatic year (Fig. 8).

In most of the years, the combined annual irrigation and total environmental water requirement were far less than the available annual streamflow (Fig. 8). The combined water requirement accounted for 12% (2001) to 87% (1997) of the total annual streamflow (Fig. 8). This suggests that, in terms of annual streamflow volume, there was an excess of water — above both irrigation water requirement and environmental water requirement, leaving the watershed for other purposes.

Intensifying water harvesting altered the streamflow hydrograph at the outlet of the watershed. It affected the amount and the timing of the peak flows and low flows at the outlet of the watershed (Fig. 9a). After water harvesting implementation, peak flows were reduced and low flows increased. Since the water harvesting ponds store and release the excess water slowly, the hydrograph lagged in time. The simulations with water harvesting with all three nutrient application scenarios provided similar streamflow hydrographs at the watershed outlet.

The decrease in peak flows and increase in low flows as a result of water harvesting implementation have positive implications for both upstream and downstream social–ecological systems. However, minor negative externalities may occur as the social–ecological system has to adjust to these new flow regimes.

Peaks flows are often associated with flooding, bank and channel erosion, and downstream reservoir sedimentation problems. Such instream morphology changes may potentially affect the distribution and abundance of stream biota (Smakhtin, 2001). Moreover, high velocity and high sheer-stress flows from flooding often cause catastrophic drift that can eliminate the standing benthic biota (Bunn and Arthington, 2002). Water harvesting, therefore, by reducing floods can reduce flood risks in downstream societies and protect species habitat from disturbance. On the other hand, reducing the floods could reduce some ecological advantages from floods. Large floods are important to stimulate spawning areas, flush out poor-quality water, mobilize and sort gravels and cobbles to enhance physical heterogeneity of the riverbed, deposit silt and nutrients on floodplain, and recharge soil moisture levels in the banks (King et al., 2003). However, large floods are not required every year to provide these ecological benefits (Richter et al., 2006), and the floods that exist after water harvesting implementation may perhaps be sufficient to provide for such ecological necessities.

Low flows provide various ecological benefits such as adequate habitat space for aquatic organisms; suitable water temperatures, dissolved oxygen, and water chemistry; soil moisture for plants; and drinking water for terrestrial animals (Bunn and Arthington, 2002; Richter et al., 2006). An increase in low flows provides wetted habitat and better

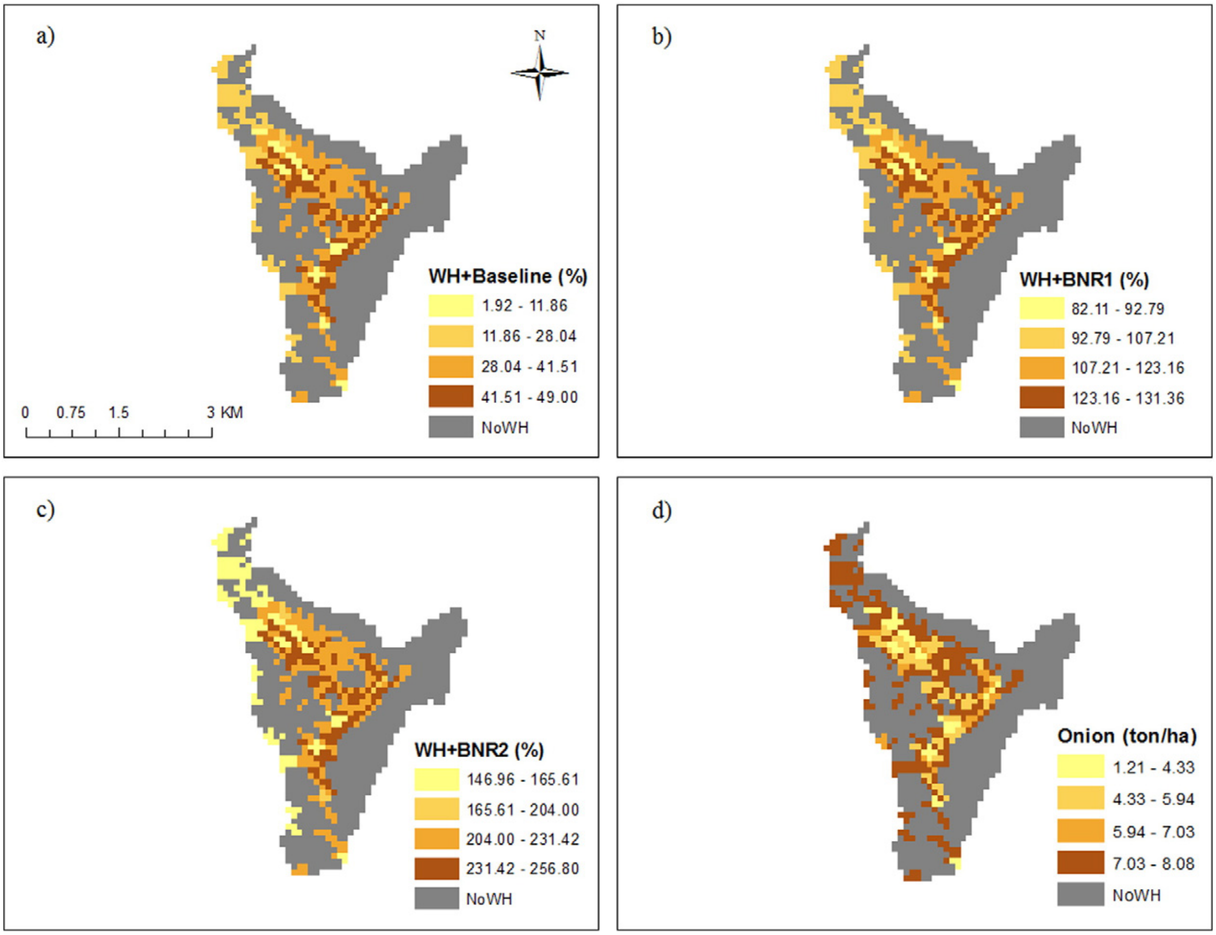

Fig. 6. Crop production with water harvesting and nutrient scenarios in typical wet year (e.g. 2001). Percent changes in teff yields with supplementary irrigation and a) baseline nutrient application, b) BNR1, and c) BNR2 scenarios compared to baseline condition teff production; and d) onion production (t/ha) with irrigation and nutrient application. WH refers Water Harvesting, and refer Table 2 for the different scenarios.

hydraulic and water-quality conditions that can improve total primary and secondary production (Bunn and Arthington, 2002), which directly influences the balance of species (King et al., 2003).

Mean monthly streamflow (1993–2007) changed substantially after water harvesting implementation (Fig. 9b). Mean monthly streamflows from May to September were reduced by 15%-93% after implementation of water harvesting. On the other hand, mean monthly streamflows from October to April increased by more than 2.5 times following water harvesting implementation. The water harvesting systems filled up during the rainy season (June to September), and supplementary irrigation for the rainfed teff occurred at the same time. This resulted in reductions in streamflow during these months. The increase in streamflow from October to April was caused by various changes in the water balance. In the late periods of the rainy season (e.g., October and November), the increase in streamflow resulted mainly from a lag in streamflow due to the storage and release effects from the water harvesting ponds. However, in the other months, the increase in streamflow was caused by return flows from various stocks in the water balance: percolation and groundwater recharge increased after water harvesting implementation, which in turn increased lateral and groundwater contributions into the streams. The annual groundwater recharge increased by more than 2 mm with the implementation of irrigation from the water harvesting ponds (SI, Fig. S3).

Implementation of water harvesting resulted in a decrease of annual streamflow volume which ranged from 14% to 33% (Fig. 9c). This suggests that implementation of water harvesting may have modest negative consequences downstream; for example, on downstream irrigation and hydropower generation. However, in some years an increase in annual streamflow volume of up to 25% was observed. This increase in annual streamflow volume was observed in years that were preceded by higher rainfall years because of storage in water harvesting ponds and other stocks from the previous years and release in the following year. For example, the highest increase in annual streamflow volume in 2002 (25%) was due to rainfall that occurred in 2001, which had the highest rainfall on record (SI, Fig. S1). This confirms water harvesting's potential of buffering climatic variability.

Table 4
Evapotranspiration (mm) and water productivity (kg/m^3) across all HRUs and seasons (1993–2007) for the baseline condition and different scenarios.

	Evapotranspiration (mm)			Water productivity (kg/m^3)		
	2.5th	Median	97.5th	2.5th	Median	97.5th
Baseline	344	436	476	0.14	0.17	0.20
WH + baseline N[a]	394	441	485	0.17	0.27	1.12
WH + BNR1	413	447	482	0.29	0.40	1.13
WH + BNR2	418	455	489	0.38	0.45	0.75

[a] WH refers water harvesting.

3.3.4. Sediment

Soil erosion is a major issue to farmers in the study watershed, causing loss of productive soils and subsequent reductions in productivity. The annual simulated sediment yield ranged from 0.2 t/ha to 197 t/ha, depending on biophysical and climatic conditions. The average spatio-temporal annual sediment yield was 21 t/ha. This finding was consistent with literature values in the Upper Blue Nile basin. Betrie et al. (2011)

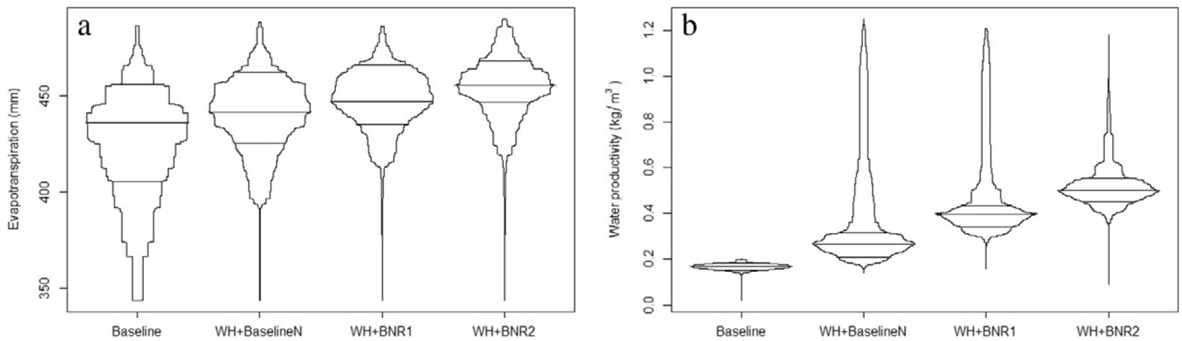

Fig. 7. Box-percentile plot for seasonal evapotranspiration and water productivity at different conditions. a) Seasonal evapotranspiration (mm) and b) water productivity (kg/m^3) of teff for the baseline condition and supplementary irrigation plus three nutrient application scenarios for all HRUs and seasons (1993–2007). Refer Table 2 for the different scenarios. The median, 25th and 75th percentiles are marked with line segments across the box. The width of the box at any height up to the 50th percentile is proportional to the percentile of that height, and the width above the 50th percentile is proportional to 100 minus the percentile.

reported that annual soil erosion in the Upper Blue Nile varies from negligible to over 150 t/ha. Setegn et al. (2009) estimated an average annual sediment yield of 0 to 65 t/ha in the Lake Tana basin. In Anjeni watershed, Setegn et al. (2010a) reported that measured average annual sediment yield was 24.6 t/ha, and their estimate was ~28 t/ha.

Implementation of water harvesting ponds considerably reduced the sediment yield to the downstream ecosystems. The sediment load leaving the watershed before water harvesting implementation was in the thousands of metric tons; however, water harvesting implementation reduced it to hundreds of metric tons (Fig. 10). Note that the y-axis in Fig. 10 is in logarithmic scale. However, since there was not much low flow during the baseline (without water harvesting) condition, there was not sediment yield in dry periods, and zero values are not plotted in Fig. 10. On the other hand, with the implementation of water harvesting ponds, there were low flows and it carried minor amounts of sediment yield in dry periods. The reduction in sediment load was related to the capacity of water harvesting structures to trap the sediment flux leaving the agricultural fields.

The capacity of the water harvesting ponds to reduce sediment yield to the downstream watersheds has both upstream and downstream benefits. Water harvesting systems can prevent soil and nutrient loss from upstream fields, thereby restoring soil fertility. For example, Gunnell and Krishnamurthy (2003) reported that in dryland peninsular India, farmers transfer fine textured tank-bed sediment from ex-situ water harvesting systems to the fields of the catchment using bullock carts to balance soil texture and optimize on-site fertility. While downstream social–ecological systems will benefit from reduced nutrient release, studies showed that nutrients (e.g., nitrogen and phosphorous) are transported to riverine ecosystems embedded through the sediment loads, and these nutrients can degrade water quality downstream (Beusen et al., 2005; Holtan et al., 1988; Ittkkot and Zhang, 1989; Lal, 2004; Ludwig et al., 1996). Therefore, by trapping sediment loads and nutrients, water harvesting ponds can improve the water quality and avoid downstream ecological problems such as eutrophication of lakes and river reaches. Moreover, they can reduce siltation of lakes and reservoirs downstream. On the other hand, siltation of water harvesting ponds will be a daunting phenomenon (cf., Tamene et al., 2006), and dredging sediment loads from water harvesting ponds to fields will be a challenging task. Releasing sediment-free water to the downstream reaches also has environmental consequences. For example, sediment-depleted water released from water harvesting ponds can erode finer sediments from the receiving channel (cf. Poff et al., 1997). This can result in progressing head-ward channel down-cutting and erosion (Chien, 1985). Habitat availability for the many aquatic species living in interstitial spaces may also decrease as a result of coarsening of the streambed.

4. Discussion

We studied the implications of intensifying water harvesting on the upstream–downstream social–ecological systems. In hydro-biophysical systems like the Lake Tana basin, we generally observed benefits for upstream as well as downstream social–ecological systems. Indeed, there are some externalities to the downstream social–ecological systems.

The benefit for the upstream social–ecological systems is mainly having more water so as to avoid crop water stress during rainy seasons and cultivate cash crops during dry seasons. As successive scenarios in this study demonstrated, water harvesting with nutrient application can increase agricultural production by up to threefold compared to the current farmers' practice. This is vital to reducing risks from climate variability and thereby increasing agricultural production. Water harvesting, therefore, can play an important role for local- to regional-scale food security and generate more income from the sale of cash crops. The additional income builds farmers' capacity to buy agricultural

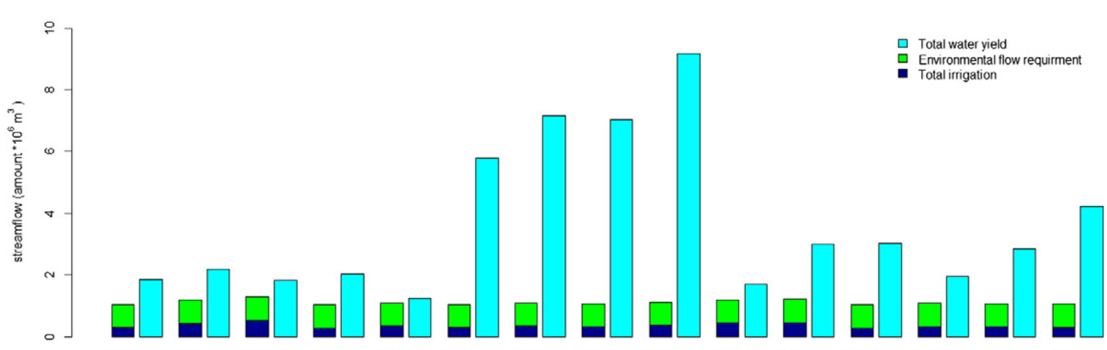

Fig. 8. Annual total irrigation, environmental water requirement and total water yield in millions of m^3.

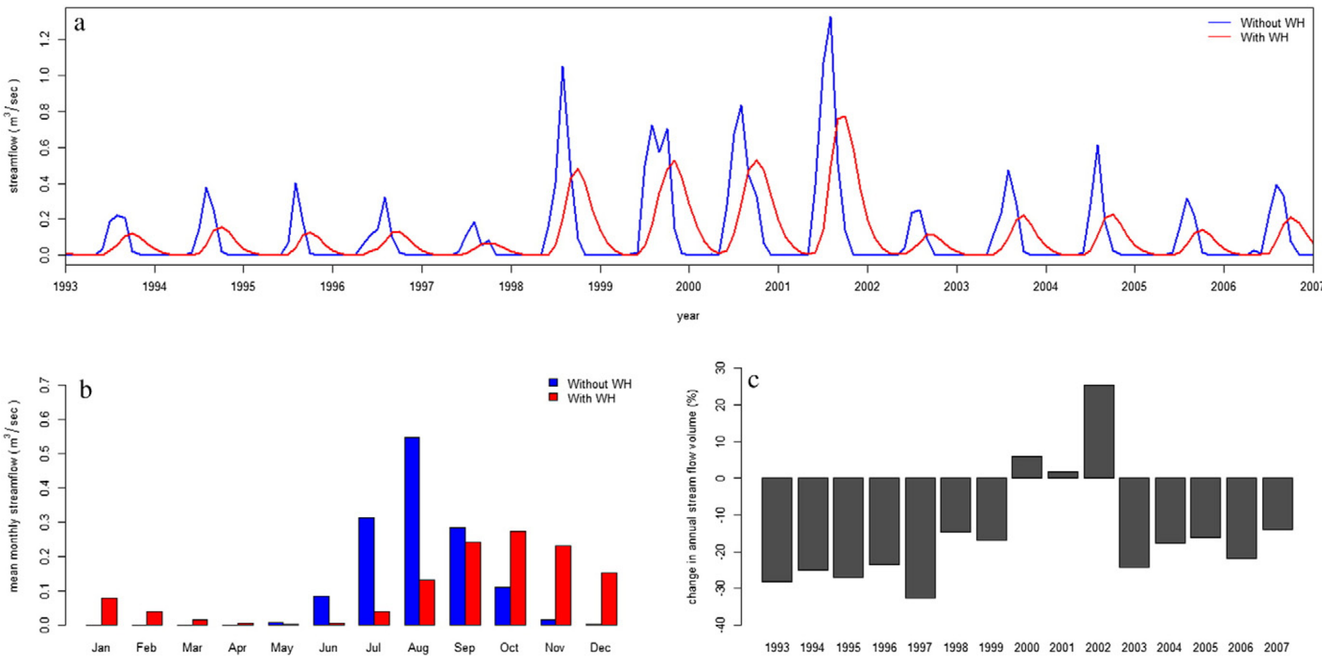

Fig. 9. Stream flow at the outlet of the watershed without and with water harvesting (WH) implementation. a) Stream flow hydrograph from 1993–2007, b) mean monthly stream flow (1993–2007), and c) change in annual stream flow volume as a result of water harvesting implementation.

inputs (e.g., fertilizer) for the next farming season. Currently, the nutrient application in sub-Saharan Africa is generally low (IAASTD, 2009). This is mainly related to risk-averse behavior – that dry spells/drought may occur and crops will fail anyway – that farmers have developed over time. Dile et al. (2013b), however, conceptually showed that having water harvesting structures that buffer climate variability can create farmer confidence to invest in agricultural inputs. This can increase overall agricultural productivity.

Most upstream benefits have a spillover effect onto the downstream social–ecological systems. For example, increased crop yield can increase food availability for the people downstream, with potentials for delivering food at relatively low costs and food sharing (cf. Pretty et al., 2003). Downstream social–ecological systems will immensely benefit from decreased flooding problems, increased low flows, and reduction in sediment influxes. Moreover, the increase in agricultural production took place on existing agricultural land. This, therefore, avoids the need for changing land use types for non-agricultural lands, which are used for other ecosystem services. These factors suggest that water harvesting can also benefit downstream social–ecological systems.

We showed that agricultural production can increase with water harvesting and nutrient application. On the other hand, fertilizer application may lead to higher nutrient concentrations in streamflows, thereby decreasing water quality. However, we also showed that water harvesting ponds can trap sediment loads and thereby reduce nutrient effluent into streams. This indicates multiple benefits of water harvesting structures in the continuum of upstream–downstream systems.

Water harvesting may have some negative externalities to downstream ecosystem services. These externalities include a reduction in annual streamflow volume of ~14% to 33% depending on climatic year, disturbance of the natural flow variability, and sediment flow. Streamflow reductions occur during the wet season, and they may not cause serious downstream ecological externalities. However, large-scale intensification of water harvesting may compromise water demand for downstream irrigation and hydropower generation. The disturbance of the natural flow variability and sediment reductions may affect the normal functioning of the ecosystems. For example, reduction of sediments could trigger streambank erosion downstream.

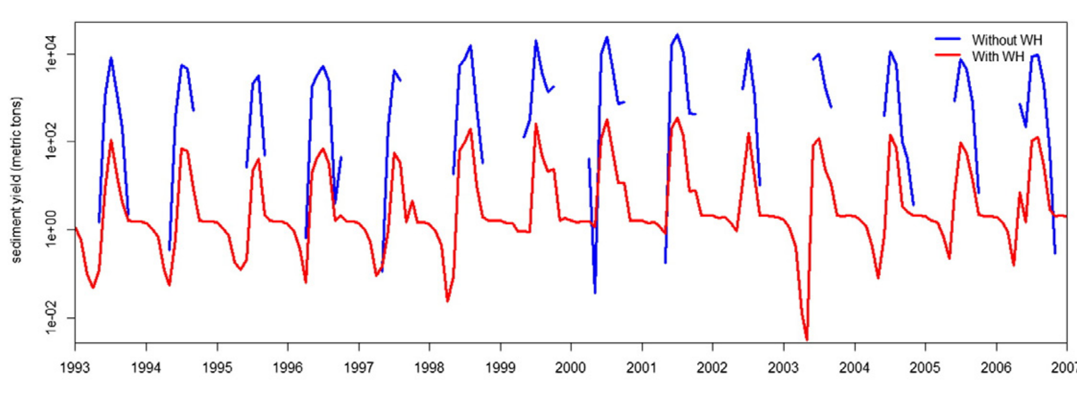

Fig. 10. Sediment yield out of the watershed (metric tons/month) with and without water harvesting. Note the y-axis is in logarithmic scale. There was not low flow during the baseline condition (i.e. without water harvesting), and hence there was not sediment during the dry periods. Since logarithm of zero is infinity, the zero values are removed from the plot. While with water harvesting, there was low flows and it transported minor sediment yield.

5. Conclusion

A DDS for determining size and location of water harvesting ponds was successfully integrated with the ArcSWAT model for a case-study meso-scale watershed in the Lake Tana sub-basin of Ethiopia. Moreover, impacts of large-scale implementation of water harvesting ponds were assessed for the case study. In general, crop yields increased substantially with water harvesting, particularly when nutrient application is increased. Another positive impact of water harvesting implementation was the reduction of sediment yield from the fields to downstream areas. It was found that water harvesting altered the water balance, generally reducing flows during the first phase of the wet season while increasing flows during dry seasons. The results presented in this study represent for a meso-scale watershed in the Lake Tana sub-basin. Adoption of water harvesting at a larger scale of intensification might have different impacts downstream. Economic feasibility and detailed impacts on the downstream ecological systems warrant thorough investigation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.10.065.

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