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Expanding sustainable land management in Ethiopia: Scenarios for improved agricultural water management in the Blue Nile

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ABSTRACT

Deforestation due to farmland expansion, fragile soils, undulating terrain, and heavy seasonal rains makes the highlands of Ethiopia vulnerable to soil erosion. The diverse terrain of the rural highlands requires spatially explicit investments in land management structures. This paper utilizes recent hydrological and meteorological data collected from the Mizewa watershed in the Blue Nile Basin of Ethiopia, as well as household survey data on farmer preferences and investments, in order to better understand the physical impact of sustainable land management activities.

The effectiveness of the simulated conservation practices (terraces, bunds, and residue management) is evaluated using the Soil and Water Assessment Tool taking into account investment decisions on different terrain types. Simulations include terracing on steep and mid-range hillsides; a mix of terracing and bunds on varying slope gradients; and a mix of terraces and residue management on varying terrain. Simulated conservation practices are evaluated at the outlet of the Mizewa watershed by comparing model simulations that take into account the limited investments that currently exist (status quo) with simulations of increased terracing and residue management activities within the watershed.

Results suggest that a mixed strategy of terracing on steep slopes and residue management on flat and middle slopes dramatically decrease surface runoff and erosion. A landscape-wide investment of terraces and bunds throughout the watershed landscape provides the greatest reduction in surface flow and erosion. However, the type and amount of investment in sustainable land management activities have different implications with respect to labor input and may be cost-prohibitive in the medium term.

1. Introduction

Continuous investments in water resource management in the Blue Nile Basin suggest a need for efficient and effective mechanisms to improve water capture, decrease erosion and increase agricultural output in the highlands of Ethiopia. Ethiopia's unique biophysical variability provides the underlying conditions for abundant freshwater resources. However, deforestation due to farmland expansion and energy needs, fragile soils, undulating terrain, and heavy seasonal rains makes the highlands vulnerable to soil erosion and gully formation in the rainy season. During the dry season in the Upper Blue Nile basin, water scarcity and low water tables cause previously perennial streams to be intermittent, affecting agricultural yields.

Approximately two-thirds of the area within the Blue Nile Basin is located in the highlands of Ethiopia. This area receives relatively sufficient rainfall (800–2200 mm per year), with the majority of rain falling during the *kiremt* rains (June–September) that supply the main *meher* cropping season. Agricultural production in the highlands is dominated by rain-fed cereal crops, which necessitates frequent soil mixing and provides very little ground cover at the start of the *meher* season, thus rendering it more susceptible to erosion and land degradation (Haileslassie et al., 2008; Werner, 1986). Earlier studies have estimated the cost of land degradation to be between 2.0 and 6.75 percent of Ethiopia's agricultural GDP per annum (Yesuf et al., 2005).

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Estimates of soil loss due to erosion vary by location. The average annual soil loss in Medego watershed in the north of Ethiopia was estimated at 9.6 metric tons ha/year (Tripathi and Raghuwanshi, 2003). Chemoga watershed in the Blue Nile Basin loses 93 metric tons per ha/year due to erosion (Bewket and Teferi, 2009). Shiferaw (2011) estimated soil loss in Borena *woreda* and found no loss in the flat plain areas to over 154 metric tons per ha/year in steeper areas.

Previous studies have examined the impact of investments in sustainable land management (SLM) in the Blue Nile basin derived implicitly from economic analyses (Schmidt and Tadesse, 2014; Pender and Gebremedhin, 2006; Holden et al., 2009; Kassie et al., 2007). However, pairing a local-level hydrological model that takes into account biophysical differences in terrain and household survey data that reports investment choice and magnitude provides greater insight as to how specific investments improve hydrological processes.

The analysis explores investment decisions on different terrain types bearing in mind current SLM practices and feasibility for expanded SLM infrastructure. Assuming that future weather patterns are similar to previous years, simulations model a variety of SLM investments over a 20-year investment period (2009–2030). Simulations include: (1) terracing on steep hillsides (slopes greater than 20°), (2) terracing on mid-range and steep hillsides (slopes greater than 5°), and terracing on mid-range and steep slopes with bund construction on flatter areas. In addition, residue management (limited livestock grazing) is simulated across flat terrain (slopes less than 5°) with terrace construction on middle and steep areas. Finally, the model simulates residue management in flat and middle slope areas (slopes between 0 and 20°) and terraces on steep terrain (greater than 20° slopes).

This analysis adds to the literature on modeling the impacts of SLM investments for several reasons. First, it presents new data and analysis from a previously ungauged watershed at the headwaters of the Blue Nile Basin. Second, it draws from a network of localized soil, weather, and runoff data in order to simulate more detailed hydrological impacts of SLM investments on different slope types within a small watershed. There are limited studies in the Blue Nile Basin that focus on investments in catchment management at a local (micro-watershed) scale. Hydrological models at the micro-watershed level are particularly important in the Ethiopia context due to the wide range of infiltration rates on agricultural plots (Descheemaeker et al., 2006b; Mwendera and Saleem, 1997; Pilgrim et al., 1988). Differences in soil texture, landuse, and slope gradients within watersheds require detailed micro-watershed modeling to identify local impacts of specific SLM investments.[2] Given this diversity, it is unrealistic to assume that results stemming from a micro-watershed case study could be applied to all agricultural areas in the Blue Nile Basin, however careful examination of other micro-watersheds with similar characteristics will benefit from detailed analysis presented in this study.

The remainder of the paper is as follows. Section 2 describes the materials and methods used for the hydrological modeling including: a review of the Soil and Water Assessment Tool, a description of the study watershed, a discussion of the model input data and calibration measurements, and an explanation of the simulations that are reported in the analysis. Section 3 discusses simulation results and explores areas of further research, while Section 4 concludes.

2. Material and methods

2.1. Model description and review

The Soil and Water Assessment Tool (SWAT) developed by the US Department of Agriculture (Arnold et al., 1998) is a commonly used hydrological model in Ethiopia. SWAT simulates the impact of land management practices on water balance and sediment yields (erosion) in watersheds with varying soils and land use over time. The model has been used across a range of catchment sizes from 0.015 km^2 (Chanasyk et al., 2003) to nearly 500,000 km^2 (Arnold et al., 2000). Kalin and Hantush (2003) reviewed the capabilities of commonly used hydrologic models utilized to simulate SLM investments and concluded that SWAT provides the ability to simulate the widest range of possible SLM alternatives in agricultural watersheds.

Watersheds in SWAT are divided into multiple sub-watersheds based on elevation data, which are further subdivided into hydrologic response units (HRUs) characterized by soil type, land use, and slope class. Runoff is predicted separately for each HRU and then routed to calculate total runoff for the watershed. A water balance equation is employed to simulate the hydrologic cycle in a watershed (or basin):

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

where SW_t is the final soil water content, SW_0 represents the initial soil water content on day$_i$, R_{day} is the total precipitation on day$_i$, Q_{surf} represents the amount of surface runoff on day$_i$, E_a is the amount of evaporation on day$_i$, W_{seep} is the amount of water that percolates into the vadose zone (area between the bottom of the soil profile and the top of the shallow aquifer) on day$_i$, and Q_{gw} is the amount of base flow on day$_i$. The number of days of the simulation is t. Equations for each of the components that make up the water balance computation are described in Neitsch et al. (2002).

SWAT calculates erosion using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1995), which utilizes the amount of runoff to simulate sediment yield and erosion. The hydrology component of SWAT estimates the surface volume (Q_{surf}) and peak runoff rate (q_{peak}) taking into account the area of the hydrologic response unit in hectares ($area_{hru}$) which is then used to estimate the runoff erosive energy variable in the MUSLE equation (Williams, 1995):

$$\begin{aligned} Sed = {} & 11.8(Q_{surf} * q_{peak} * area_{hru})^{0.56} \\ & * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG \end{aligned} \quad (2)$$

where sediment yield (Sed) on a given day is a function of Q_{surf}, q_{peak}, $area_{hru}$, as well as key soil characteristics: the soil erodibility factor (K_{USLE}), the C_{USLE} which represents the land cover and management factor (i.e. cropped versus fallow land), the support practice factor (P_{USLE}) which distinguishes among different land management practices (i.e. terrace systems), the topographic factor (LS_{USLE}) or expected ratio of soil loss per unit area from a field slope, and the coarse fragment factor ($CFRG$) which takes into account the percent of rock in the first soil layer. A detailed description of the computation of each variable is provided in Neitsch et al. (2005).

In general, past analyses on SLM infrastructure investment in Ethiopia suggest a positive effect on water balance in the watershed. Desta et al. (2005) evaluated plot level data of bund investments over time (bunds ranging from 3 to 21 years old) in Dogu'a Tembien, Tigray region and found a 68 percent reduction in annual soil loss in the watershed since the introduction of stone bunds. Using on-farm experimental sites in a variety of agro-ecological zones, Herweg and Ludi (1999) found that SLM

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[2] A 1998 land conservation project implemented in Tigray, Ethiopia illustrated the localized effects of certain conservation techniques whereby specific investments were successful in some areas but completely failed in other locations within Tigray (Nyssen et al., 2003).