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Hydrological modeling of sustainable land management interventions in the Mizewa watershed of the Blue Nile Basin

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1. ABSTRACT

According to the International Water Management Institute (IWMI), the Blue Nile basin is one of the least planned and managed sub-basins of the Nile (IWMI, 2008). Previous studies have examined the impact of investments in sustainable land and watershed management (SLWM) in the Blue Nile basin derived implicitly from economic analyses (Schmidt and Tadesse 2012; Pender and Gebremedhin 2006; Holden et al. 2009; Kassie et al. 2007). However, further examination using a hydrological model that takes into account biophysical differences in terrain, investment choice and magnitude (i.e. terraces vs. bunds implemented on only steep terrain vs. middle and steep terrain) within the watershed will provide greater insight as to how specific investments improve hydrological processes, and their explicit impact on agricultural productivity.

This analysis utilizes recent hydrological and meteorological data collected from the Mizewa watershed in order to better understand the physical impact of SLWM investments. The effectiveness of the simulated conservation practices (terraces, bunds, and residue management) are evaluated using the Soil and Water Assessment Tool (SWAT) model taking into account investment decisions on different terrain types. Simulations include: 1) terracing on steep hillsides (slopes greater than 20 degrees); 2) terracing on mid-range and steep hillsides (slopes greater than 5 degrees); 3) a mix of terracing and bunds on varying slope gradients; 4) residue management on all agricultural fields; and 5) a mix of terraces and residue management on steep and mid-range terrain where a majority of agricultural activity takes place. 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 the benefits of residue management practices were more important for less steep areas; while a mixed strategy of terracing on steep slopes and residue management on flat and middle slopes dramatically decreased surface runoff and erosion. A comprehensive 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 SLWM have different implications with respect to labor input and utilization of agricultural land. It is important to note that although simulations suggest that a landscape-wide approach reaps the greatest long-term benefits, it is important to understand the costs of such an investment.

2. INTRODUCTION

Continuous investments in water resource management in the Blue Nile Basin suggest a need for efficient and effective mechanisms to improve water capture and 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 make the highlands of Ethiopia 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 abundant rainfall (800 to 2,200 millimeters per year), with the majority falling during the *kiremt* rains (June-September) that supply the main *meher* cropping season. Rainfall varies geographically and seasonally in the basin, with dry periods that may significantly reduce crop yields and lead to seasonal food insecurity (Schmidt and Dorosh, 2009). Agricultural production in the highlands is dominated by cereal crops, which necessitates frequent soil mixing and provides very little ground cover during the kiremt rains, thus rendering it more susceptible to erosion and land degradation (Haileslassie et al. 2005; 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). Holden and Shiferaw (2002) and Shiferaw and Holden (1998) assessed farmers' perceptions of the costs of land degradation and compared these to the results of an analysis using the universal soil loss equation to estimate the impact of soil erosion on overall crop yields. The analytical results suggested that average rates of land productivity decline were twice that of perceived rates, whereby 1.1 percent of productivity is lost per year when no fertilizers are used, compared to a loss of 0.55 percent per year when fertilizer application is efficient (similar to farmers perceived loss estimates). In addition to the on-site costs of land degradation, the country also incurs off-site costs with siltation of dams, reservoirs, wetlands, lakes, and productive farmlands in foot slope areas (Yesuf et al. 2005).

In terms of soil loss due to erosion, estimates vary by location, which reflects the varying Ethiopian landscape and soil characteristics within and between woredas. Hurni et al. (2010) measured soil erosion rates on test plots and estimated a loss of 130 to 170 metric tons per hectare per year on cultivated land. 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). The average annual soil loss due to erosion in the Chemoga watershed in the Blue Nile Basin was estimated at 93 metric tons ha/year (Bewket and Teferi, 2009). Shiferaw (2011) estimated soil loss in Borena woreda in south Wollo using the Revised Universal Soil Loss Equation (RUSLE, which allows for spatial modeling of soil loss) and found that annual soil loss ranged from no loss in the flat plain areas to over 154 metric tons ha/year in some steeper areas.

According to the International Water Management Institute (IWMI), the Blue Nile basin is one of the least planned and managed sub-basins of the Nile (IWMI, 2008). Previous studies have examined the impact of investments in sustainable land and watershed management (SLWM) in the Blue Nile basin derived implicitly from economic analyses (Schmidt and Tadesse 2012; Pender and Gebremedhin 2006; Holden et al. 2009; Kassie et al. 2007). However, further examination using a hydrological model that takes into account biophysical differences in terrain and investment choice and magnitude (i.e. terraces vs. bunds implemented on only steep terrain vs. middle and steep terrain) within the watershed will provide greater insight as to how specific investments improve hydrological processes, and its explicit impact on agricultural productivity. This analysis focuses on the impact on runoff and sediment capture of a variety of SLWM investments on different slope types (steep, midlands, and flatland) within the Mizewa watershed in Fogera woreda in the South Gondar zone of Amhara region in north central Ethiopia.

The study utilizes recent hydrological and meteorological data[1] (stream flow, rainfall, weather, soil moisture, and groundwater measurements) collected from the previously ungauged Mizewa watershed. The Soil and

[1] Data collected by the International Water Management Institute (IWMI) under the Nile Basin Development Challenge (NBDC).

Water Assessment Tool (SWAT) developed by the US Department of Agriculture (Arnold et al. 1998) is utilized to simulate soil moisture, erosion, and runoff processes in order to better understand the physical impact of SLWM investments.

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. Assuming that future weather patterns are similar to previous years, simulations model a variety of SLWM investments over a 20-year investment period (2009-2030). The analysis takes into account investment decisions on different terrain types. The simulations include: 1) terracing on steep hillsides (slopes greater than 20 degrees), 2) terracing on mid-range and steep hillsides (slopes greater than 5 degrees), 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 degrees) with terrace construction on middle and steep areas. Finally, we simulate residue management in flat and middle slope areas (slopes between 0-20 degrees) and terraces on steep terrain (greater than 20 degree slopes). Results suggest that the benefits of residue management practices were more important for less steep areas; while a mixed strategy of terracing on steep slopes and residue management on flat and middle slopes dramatically decreased surface runoff and sediment. Parallel terraces in middle and steep areas significantly reduced surface runoff and sediment yield and improved groundwater flow whereby average surface flow decreased by 42 percent and erosion was reduced by 90 percent.

3. MODEL DESCRIPTION AND REVIEW

A commonly used hydrological model in Ethiopia is the Soil and Water Assessment Tool (SWAT) developed by the US Department of Agriculture (Arnold et al. 1998). 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). 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. Geographic Information Systems (GIS) and spatial data are utilized to divide the watershed into unique HRU's by slope class, soil characteristics and land cover. Runoff is predicted separately for each HRU and then routed to calculate total runoff for the watershed. SWAT uses a water balance equation to simulate the hydrologic cycle in a watershed (or basin):

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

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). MUSLE is a modified version of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965, 1978), which employs the amount of runoff to simulate sediment yield and erosion (the USLE models sediment using rainfall as the primary indicator of 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 are then used to estimate the runoff erosive energy variable in the MUSLE equation (Williams, 1995):

$$Sed = 11.8(Q_{surf} * q_{peak} * area_{hru})^{0.56} * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG$$

where sediment yield (Sed) on a given day is a function 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. (2000).

Although hydrological data that span pre- and post- SLWM program interventions are sparse in Ethiopia, a variety of studies have evaluated investments on stream flow patterns in the Blue Nile Basin and other regions of Ethiopia. For example, Tesfahunegn et al. (2011) used SWAT to simulate a variety of conservation measures, including afforestation and terracing, in the Mai-Negus catchment in Tigray region and obtained results that suggest a mix of measures provides the largest reduction in runoff and sediment yield during the rainy season. Bewket and Sterk (2005) analyzed stream flow patterns from 1960-1999 in the Chemoga watershed of the Blue Nile basin and attribute land cover change due to cropland expansion and overgrazing to significant declines in dry season stream flow. A modeling study in the Ziway-Shala basin in south-central Ethiopia predicted an 8 percent decrease in outlet discharge during peak flows if the existing cultivated and grazing lands were converted into woodland (Legesse et al., 2003). A variety of soil and water conservation measures, including stone bunds, check dams and abandonment of post-harvest grazing, in the May ZegZeg catchment in north Ethiopia were shown to result in higher infiltration rates and reduced runoff volumes, which permitted farmers to plant crops in previously active gullies (Nyssen et al. 2010). Betrie et al. (2011) used a SWAT model at a larger geographic scale to model the Upper Blue Nile basin to understand the effect of filter strips, stone bunds, and reforestation on overall sediment loads and found reduced sediment yields at the sub-basin and basin outlets.

However, there are limited studies at the plot and experimental field level of the hydrological impacts of SLWM investments in Ethiopia. Desta et al. (2005) evaluated plot level data of bund investments over time (bunds ranging from 3 – 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) measured the impact of bunds, grass strips, and double ditches on runoff and crop yield. They found that investments reaped benefits in terms of reductions in soil loss and runoff (especially in semi-arid watersheds). However, their study showed that the resultant increases in agricultural yields did not outweigh the estimated costs of the soil conservation investments. Descheemaeker et al. (2006) examined the impact of enclosures as a soil conservation measure in Tigray and found that closed areas of afforestation were highly efficient mechanisms of sediment trapping.

In general, past analyses on SLWM infrastructure investment in Ethiopia suggest a positive effect on water balance in the watershed, whereby increased infiltration and soil water content and decreased surface runoff are a result of well-maintained investments. Improvements in water capture and infiltration lead to decreases in runoff volume, as well as moderating peak flows at the watershed outlet and decreasing sediment transport after large storms.

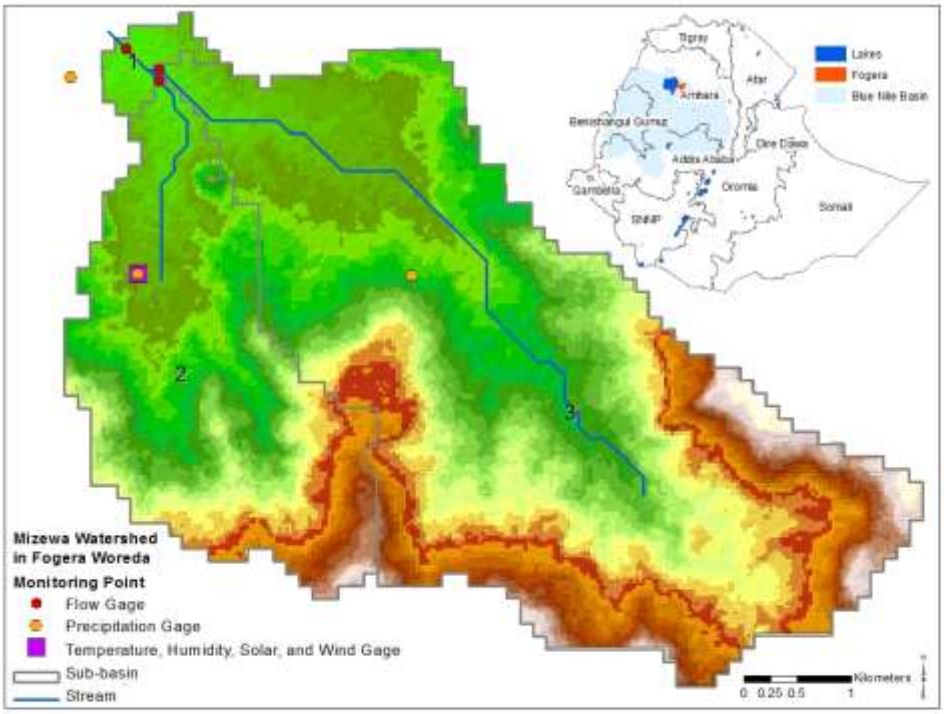
This analysis adds to the literature on modeling the impacts of SLWM investments on soil and water for several reasons. First, it presents new data and analysis from a previously ungauged watershed at the headwaters of the Blue Nile Basin. Second, it draws from a network of localized soil, weather, and runoff data in order to simulate the hydrological impacts of SLWM investments on different slope types within the watershed. There are limited studies in the Blue Nile Basin that focus on investments in catchment management at a local (micro-watershed) scale. Better understanding the relationship between these investments and surface runoff and sediment yield in the wet season and groundwater flow in the dry season are of importance to achieving overall agricultural production gains in a predominantly subsistence farming rural economy.

4. STUDY AREA DESCRIPTION AND MODEL INPUT DATA

The rain-fed agricultural practices that characterize the highlands of Ethiopia, as well as the stream flow contribution to the Nile River are defined by the main kiremt rainy season that occurs from June through September. Approximately 60 to 70 percent of annual precipitation in the Upper Blue Nile basin falls during this rainy season, and greater than 80 percent of annual runoff occurs during this time (Eldaw, et al. 2003; Conway 2000). Runoff from the Upper Blue Nile and the Atbara river basins supply approximately 70 percent of the annual flow of the Nile into Egypt, with a majority of the runoff provided during the rainy season (Yates and Strzepek 1998). The estimated 30-year annual mean temperature and evapotranspiration in the Upper Blue Nile is approximately 18.5 degrees C (varying 2 degrees throughout the year on average) and 1100 mm, respectively (Kim et al., 2008; Kim and Kaluarachchi, 2008)

The Mizewa watershed is situated in Fogera woreda (district) on the eastern shore of Lake Tana in the northeast of the Blue Nile basin (Figure 1). Fogera woreda consists of flat flood plains that make up the lowlands, as well as a midland geography characterized by steeper rock inselbergs and undulating hills. The altitude ranges from 1,784 to 3,600 meters above sea level (masl), with rainfall ranging from approximately 1,000 mm per year on the plains to 1,500 mm at higher altitudes. While the lowlands near Lake Tana have been converted to rice cultivation during the last 5 years, midland agriculture consists primarily of cereal grain production. The Mizewa watershed is upstream of the flood plains, with altitude ranging from 1,850 to 2,370 masl. The hilly catchment is characterized by teff, maize and barley production which make up 47, 41, and 11 percent of cultivated area in the watershed, respectively (Table 1).

Figure 1—Mizewa watershed, elevation, and streambed



Source: Authors' calculations

Table 1—Production and predominant crop type in Fogera woreda

	Hectares per HH	Total Hectares	Share of total area	Percent farmers cultivating crop	Mean area of farmers cultivating crop
Teff	0.79	134.2	0.47	0.83	0.79
Maize	0.62	118.5	0.41	0.93	0.62
Barley	0.41	31.1	0.11	0.37	0.41
Potatoes	0.18	2.0	0.01	0.05	0.18
Wheat	0.20	0.8	0.00	0.02	0.20
Sorghum	0.17	0.5	0.00	0.01	0.17

Source: Authors' calculations

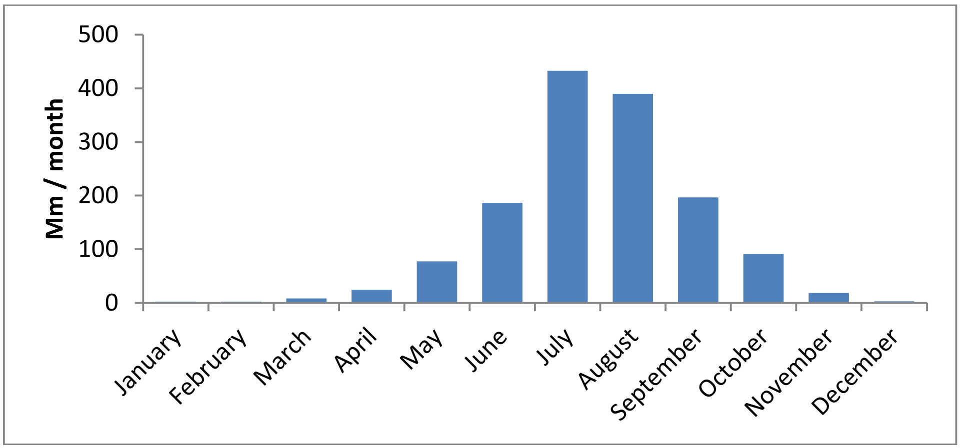
Fogera woreda has 77 perennial and 38 intermittent streams. Farmers utilize these streams for agricultural production purposes by creating traditional diversions or employing small pumps for irrigation. In the floodplains of the woreda, the water table is relatively shallow, ranging from 2 to 4 meters. Farmers in the flat area of the watershed identified flooding as a major problem during the kiremt rains with frequent waterlogging of maize. Although there are many rivers and the water table is shallow in this area, farmers reported that water scarcity is a major issue during the dry season because of upstream irrigation.

Farmers in the midland area of the Mizewa watershed use a variety of soil conservation practices, including terracing, rainwater harvesting structures (trapezoidal ponds lined with geomembranes), afforestation, and area enclosures to slow runoff during the wet season. The water table is significantly deeper in the midlands, ranging from 12 to 16 meters in depth. However, farmers identified water shortages during the dry season as a major challenge, pointing to the drying up of one of the tributary rivers (Ginde Newr) during the dry season as evidence of this trend (Zemadim et al., 2012).

The watershed modeled in this study encompasses the Mizewa River and is approximately 27 km^2 in area. For employing the SWAT for this study, the Mizewa watershed was divided into 3 sub-watersheds that were derived from a digital elevation model (DEM) and the stream network. Upstream of the primary flow gauge, the river divides into two main tributaries. The larger tributary forms the Mizewa River and has a catchment area of 18.8 km^2, while the second comprises the Zinjero Gidel (or Ginde Newr) River, with a catchment area of 7.4 km^2 (sub-watershed 3 and 2 respectively, depicted in Figure 1). The last sub-watershed encompasses the flatter area that leads to the primary outlet gauge at the Mizewa bridge (sub-watershed 1 in Figure 1).

Four precipitation gauge stations located at Addis Zemen, Infranz, Bahir Dar, and Debre Tabor have the longest precipitation data series near Fogera woreda. Rainfall data collected at the Bahir Dar station from 1961 to 2011 show a uni-modal annual rainfall pattern (Figure 2). Data from the flow gauging stations installed at the Ribb and Gumara rivers located in Fogera woreda show that the annual pattern of flow levels follows the annual rainfall pattern, whereby July and August experience the greatest runoff volumes, and minimum runoff volumes occur between March and April for both rivers (Zemadim et al., 2012).

Figure 2—Average Monthly Precipitation (Bahir Dar: 1961 – 2011)



Source: Authors' calculations

From June through August of 2011, a network of data gauges were installed in the Mizewa watershed. These included soil moisture probes; automatic and manual stream-level gauges; an automatic weather station that monitored rainfall, temperature, atmospheric pressure, humidity, wind speed and direction, and solar and net radiation; manual rain gauges; and shallow ground water monitoring devices (see Appendix Table 1). In an effort to collect data that was representative of the entire watershed, a detailed land use and land cover survey was conducted using handheld GPS units. The data were then used to create a cadastral map of the watershed (see Taffese, 2011 for details on data collection), which supported the identification of appropriate gauge (precipitation, soil moisture, ground water) locations installed along two transects covering a range of elevations and land use typologies.

Manual stream-level gauges (stage boards) were installed on the Mizewa and the Zinjero Gedel upstream confluences and an automatic stream-level gauge was installed at the watershed outlet (a detailed description of network installment can be found in Zemadim et al., 2012). The automatic stream-level gauge was used for model calibration, while the manual upstream gauges were used for validation of the model. After evaluation of soil and groundwater data, this study used data from the most reliable stations of the data network. (Several soil moisture and groundwater monitoring stations were vandalized during data collection.)

Finally, the world soil classification data developed by the Food and Agricultural organization (FAO) is used as the soil input to the SWAT model. The soil map based on the FAO soil classification from the Blue Nile basin categorizes only one soil group (Haluvi soil) in the Mizewa watershed. Haluvi soil is described as comprising a high percentage of sand with high hydraulic conductivity.

5. CALIBRATION AND VALIDATION OF THE SWAT MODEL

Parameter calibration was completed using one year of data collected at the outlet of the Mizewa watershed. A three year warm-up (2009 – 2011) period utilized long-term weather data from the Bahir Dar weather station in order to initialize the model. Model predictions are evaluated after the 3 year warm-up period and three months (August 2011 – October 2011) of simulation using Mizewa weather stations in order to approach reasonable starting values for the model state variables. River level height was collected from August 2011 through November 2012 in order to capture an entire rainy season in the Mizewa watershed. This was then converted to flow using a rating equation.

Calibration and verification were performed on the simulation period ranging from November 2011 to November 2012. Several statistics including the Nash-Sutcliffe prediction efficiency (E_{NS}), coefficient of determination (R^2), Index of Volumetric Fit (IVF), and graphical plot were used to compare model predictions against the observed values. The Nash-Sutcliffe coefficient ranges from $-\infty$ to 1:

$$E_{NS} = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - Q_o)^2}$$

where Q_o is the mean observed flow series in the calibration period, Q_m^t is modeled discharge at time t , and Q_o^t is observed discharge at time t . A value of 1 corresponds to a perfect prediction of modeled discharge to the observed data (Nash and Sutcliffe, 1970). As the coefficient approaches 0, the model predictions are as accurate as the mean of the observed data, whereas a negative value occurs when the observed mean is a better predictor than the model[2]. An E_{NS} value greater than 0.5 is considered acceptable (Moriasi et al. 2007; Santhi et al. 2001)

Similarly, the R^2 value is an indicator of strength of relationship between the observed and simulated values. Typically, R^2 values of greater than 0.5 are considered acceptable when simulating agricultural watersheds (Moriasi et al. 2007; Van Liew et al. 2003). The IVF is a simple ratio of the total simulated discharge volume to the corresponding total observed volume and provides a measurement of long term water balance within the watershed.

The combination of a genetic algorithm auto calibration tool (Deb, 2001), as well as manually adjusted parameter values for the simulation period from August 2011 to November 2012 provided the highest E_{NS} and R^2 values within the bounds of the IVF (objective value of 1 so that total simulated and observed runoff volume are comparable). Calibration parameters identified as problematic during the sensitivity analysis, as well as parameters identified as problematic after a review of SWAT model analyses done elsewhere in the highlands of Ethiopia were adjusted to improve the model fit to the observed flow. The calibration parameters are described in Table 2. In addition, Ashagre (2009) collected detailed cropping data in the nearby Anjeni watershed. We adopt this crop calendar in order to ensure that planting, growing and harvesting seasons and their respective effects on landcover were correctly reflected in the model (see Appendix Table 2).

As shown in Table 2, parameters for the SWAT were adjusted to better fit observations. The baseflow alpha factor (Alpha_BF), an index of groundwater flow response to changes in recharge (Arnold et al. 2009), was adjusted to 0.001 to simulate Mizewa land characteristics that exhibits a slow response to recharge. The SCS runoff curve number (CN2), used to predict direct runoff or infiltration as a function of the soil's permeability, land use, and antecedent soil water conditions, was reduced between 10 and 19 percent in order to take into account the higher infiltration rate suggested in the observed data. The threshold depth of water in the shallow aquifer required for base flow to occur (GWQmin), the threshold depth of water in the shallow aquifer for percolation to deep aquifer to occur (Revapmn), and the groundwater delay (GW_delay) were modified to improve model predictions of base flow, as well as flow during the dry season. GWQmin was increased in order to generate groundwater storage capacity, while Revapmn was adjusted in order to allow greater movement of water from the shallow aquifer to the unsaturated zone (Arnold et al., 2009).The GW_delay was revised to 0.5 to reflect the lag time between the water that moves from the lowest depth of the soil profile into the shallow aquifer in the less sandy areas of the watershed.

The soil evaporation compensation factor (ESCO) was reduced to 0.5 in order to account for greater evapotranspiration from lower soil levels. Finally, the saturated hydraulic conductivity (Sol_K), a measure of the ease of water movement through the soil, and the available water capacity of the soil layer (Sol_AWC) were adjusted to improve subsurface and surface flow response respectively. The USLE practice factor was adjusted to reflect previous analysis of sediment management modeling in the Blue Nile Basin (Betrie et al., 2011), given that observed sediment data for calibration were not available at the time of this study.

[2] Residual variance (described by the numerator in the equation) is larger than the observed data variance (described by the denominator).

Table 2—Parameters calibrated in model simulation

Variable name	Variable description	Units	Default value	Lower bound	Upper bound	Calibrated value
Alpha_BF	Baseflow alpha factor	Days	0.048	0	1	0.001
CN2*	SCS runoff Curve Number		n/a	-0.1	0.1	-0.19 - 0.0
GWQmin	Threshold depth of water in the shallow aquifer for return flow to occur	mm H_20	0	0	5000	700 - 1000
GW_delay	Groundwater delay	Days	0	0	500	0.5
Revapmn	Threshold depth of water in the shallow aquifer for percolation to deep aquifer to occur	mm H_20	1	0	500	0.001
ESCO	Soil evaporation compensation factor		0.95	0.001	1	0.5
Sol_k*	Saturated hydraulic conductivity	mm/hr	n/a	-0.5	1	-0.4 - 0.0
Sol_AWC*	Soil layer available water capacity	mm H_20 /mm soil	n/a	-0.5	0.5	0.19 - 0.22
USLE_P	USLE practice factor		n/a	0	1	0.40 - 0.75

Source: Authors' calculations

* CN2, Sol_k and Sol_AWC parameter values expressed as percent change from default values.
Note: Lower and upper bounds reported by Arabi et al. (2007), Santhi et al. (2006), Van Liew (2007).

The model was calibrated at daily, weekly and monthly time steps. Surface and base flow were calibrated simultaneously. Simulated results suggest that temporal dynamics are important in the overall hydrologic behavior of the watersheds. Similar to findings by Liu et al. (2008), daily flow simulations did not capture interflow that was developing and occurring over longer periods, requiring hydrographs consisting of weekly sums to capture comprehensive stream responses to rainfall events. Calibrated weekly peak flows are well-represented, with the exception of the first event, whereby the model anticipates time to concentration[3] as the first week of July, which results in a lower overall ENS and R^2 values (Table 3, Figure 3). The monthly simulated and observed flow accurately depicts runoff, and reveals that hydrologic processes and flow regimes in SWAT have a good fit with observed monthly flow data.

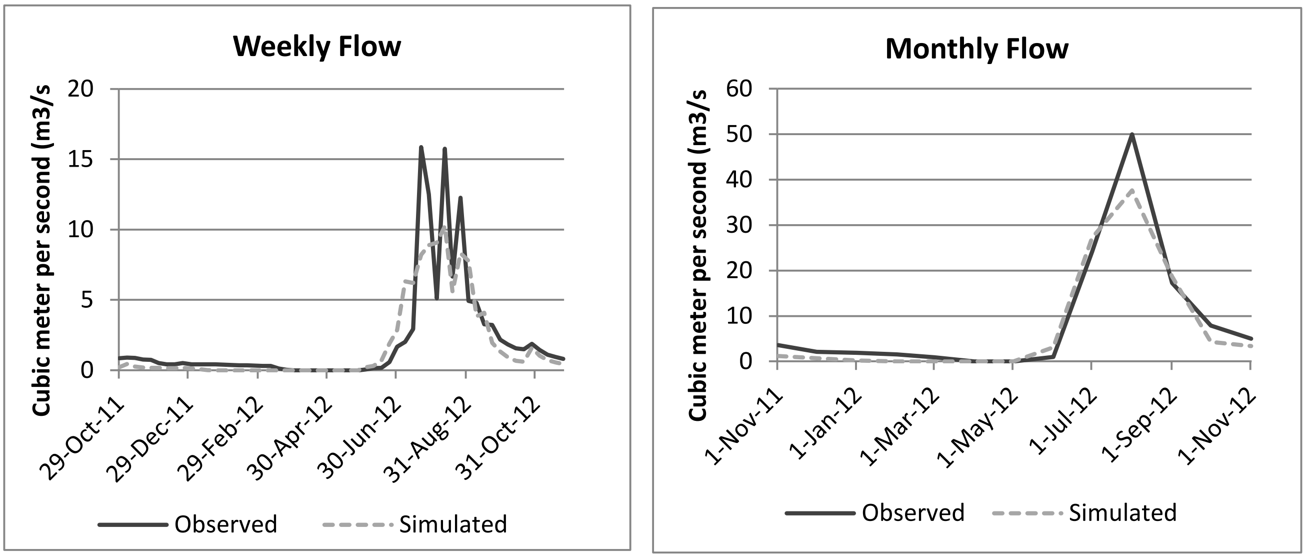
Table 3—Nash-Sutcliffe coefficient and R^2 for calibration and validation of outlet discharge

	Calibration			Validation		
	E_{NS}	R^2	IVF	E_{NS}	R^2	IVF
Daily	0.43	0.44	83.9	0.22	0.27	64.6
Weekly	0.75	0.77	83.5	0.56	0.71	64.3
Monthly	0.92	0.94	83.7	0.63	0.81	64.4

Source: Authors' calculations

[3] The time needed for water to flow from the most remote point in a watershed to the watershed outlet; as a function of the topography, geology, and land use within the watershed

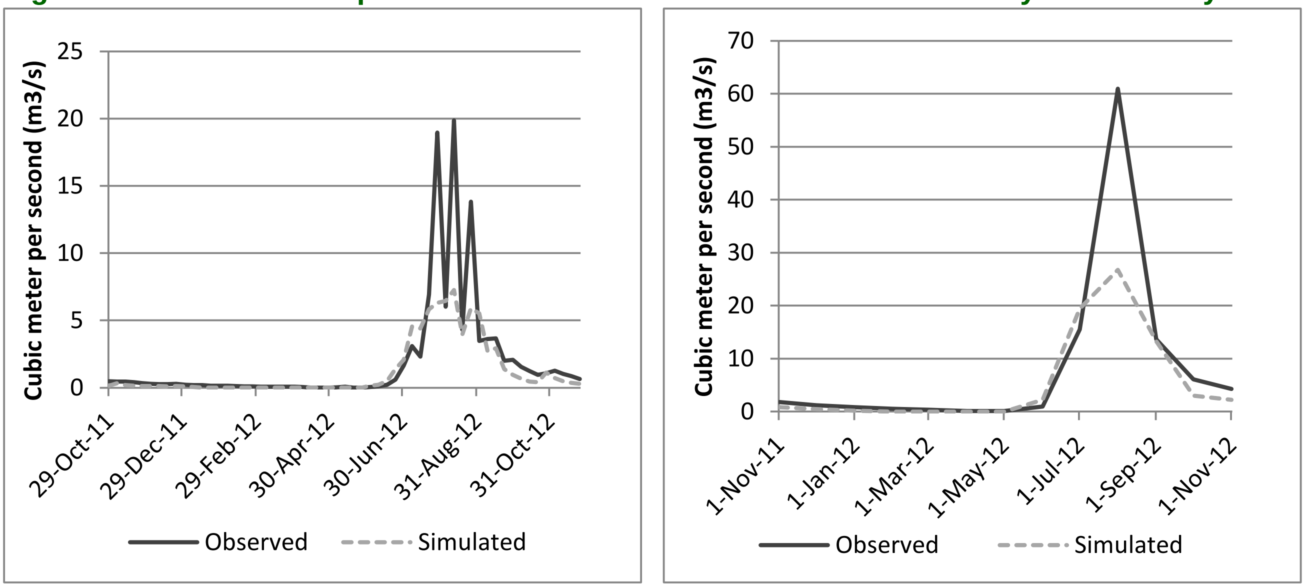
Figure 3—Calibration comparison between observed and simulated weekly and monthly stream flow



Source: Authors' calculations

After model calibration, validation was performed using discharge data from the flow measurements collected at the upstream confluence of the Mizewa watershed (associated with sub-watershed number 3, Figure 1). Model validation was completed on the calibrated parameter values to test the accuracy of the model prediction from a different observational dataset than the observed values used in the calibration. The model fit for these data values suggest that the calibrated parameters are appropriate for Mizewa watershed as reported by the predicted and observed data fit using E_{NS} and R^2 to test model validity (Table 3, Figure 4).

Figure 4—Validation comparison between observed and simulated weekly and monthly stream flow



Source: Authors' calculations

Comparing the observed flow measurements at the outlet (calibration) and sub-basin 3 reveals that an important share of runoff is infiltrated in the area of sub-basin 1 and 2 that is located at a lower elevation than sub-basin 3. For example, total observed peak monthly runoff at the watershed outlet is 50 m^3/s in August, whereas peak monthly runoff at sub-basin 3 amounted to 61 m^3/s in August. This is in part due to topographic features of the watershed. Sub-basin 3 has an overall steeper slope with undulating hills in comparison to sub-basins 1 and 2 near the outlet which consists primarily of flat pasture land. In addition, during high rainfall events, data collection of river height may be overestimated due to manual data collection in sub-basin 3 and the uneven flow current. Given these differences in topography, model calibration values accurately simulate weekly and monthly peak flows, whereas validation is less precise at simulating peak flows.

6. SIMULATING SLWM INVESTMENTS

In order to investigate the longer-term impacts of SLWM investments on soil moisture and runoff at the watershed or landscape level, it is important to understand hydrologic conditions of the study watershed. Hydrologic modeling provides key insights into management decisions where sparse measuring networks and relatively short data records are available. Kalin and Hantush (2003) reviewed the capabilities of commonly used hydrologic models utilized to simulate SLWM investments and concluded that SWAT provides the widest possibility of SLWM alternatives in agricultural watersheds. Arabi et al. (2007) reviewed SLWM hydrological modeling literature and suggest a standard procedure for representing specific investments in SWAT, whereby key model parameters are adjusted in order to simulate different investment decisions. The simulations (parameter adjustments pertaining to specific investments) modeled in this paper are drawn from published literature pertaining to SLWM simulation in hydrological models, including work by Arabi et al. (2007) and Neitsch (2005). In addition, this study uses documented local research experience in the Ethiopian highlands to select appropriate SLWM interventions and parameter modifications (Hurni 1985; Herweg and Ludi 1999; Gebremichael et al. 2005; Betrie et al. 2011). For example, Nyssen et al. (2010) collected combined measurements at the May ZegZeg catchment outlet (a 200 ha. representative watershed of the northern highlands in Ethiopia) with runoff measurements at plot scale, and calculated a runoff curve number (CN) for various land uses and land management techniques. Similarly, Descheemaeker et al. (2008) evaluated 27 test plots to calculate runoff curve numbers for hillslopes in Tigray region in different stages of vegetation restoration. Herweg and Ludi (1999) and Hurni (1985) used field trials of different soil and water conservation technologies to test a host of parameter values in the Ethiopian highlands.

Given that precipitation data from Mizewa watershed were collected for one year at the time of this study, we use the long term precipitation data collected in Bahir Dar by the Ministry of Water and Energy from 1990 to 2011 in order to simulate the effects of SLWM investments. The Global Weather Data for SWAT database provided air temperature and solar radiation, wind speed, and relative humidity data inputs based on satellite data and reported weather data from Bahir Dar and Addis Zemen weather stations. Assuming weather patterns display similar trends to previous years, SLWM simulations are evaluated over 30 years from 2009-2030. This analysis models a scale of investment decisions in order to take into account tradeoffs in labor and land investment. For example, terraces are modeled under three scenarios: 1) terraces built on only steep land (greater than 20 degree slope gradient) in the watershed; 2) terraces built on steep and mid-range slope gradients (5-20 degrees); and 3) a mix of terraces and bunds across the entire watershed landscape. Given that terraces and bunds require labor investments, residue management is another strategy that is less labor intensive, but requires grazing limitations on agricultural land. We simulate residue management under two scenarios: 1) assuming that 0.5 - 1.0 mt/ha of residue is left on flat agricultural fields between harvest and planting seasons, while also maintaining terraces on middle and steep areas; and 2) assuming that 0.5 - 1.0 mt/ha residue is left on agricultural fields in flat and mid-range slopes, while steeper slopes (greater than 20 degree gradient) receive terraces. Although contour farming is often modeled as a low cost intervention, it is a traditional method of soil conservation used in Ethiopia and most farmers in Mizewa have been contour farming for decades, thus we consider this a baseline condition.

Terracing and bunds

A variety of agricultural development programs have proposed building terraces in order to control runoff and erosion in the Ethiopian highlands. These terraces are usually built of stone and constructed as level strips built perpendicular to a slope and along the natural contours of the land. Parallel terraces segment fields into separate drainage areas which reduce the length of the slope and decrease the velocity of water runoff. Given that surface runoff is slowed, increases in potential water infiltration allows precipitation to be conserved on the field or removed via drainage areas (grassed waterways, deeper furrows in the land, etc.) in a more controlled manner. Assuming that terraces are well-maintained and constructed taking into account farming practices; they can prevent gully development, reform the land surface by trapping topsoil that would be lost through erosion, and reduce flooding downstream by slowing rainfall runoff.

Similar to terracing, soil and stone bunds are another SLWM investment that in the short-term reduces slope length and increase deposition through small retention basins. The medium and long term impacts (assuming bunds are well-maintained) include reducing steep cropland through formation of bench terraces and increasing vegetation cover (Bosshart 1997 and Desta et al. 2005). According to Chandy (2004), bunds are appropriate for areas with up to 8 percent slopes, while terraces are best suited for slopes greater than 5 percent (Humberto Blanco-Canqui and Lal 2008; Chandy 2004). Bunds are usually placed from between 5 meters apart on steep land to 30 meters apart on more gently sloping land. Hurni (1985) and Herweg and Ludi (1999) suggest spacing bunds and terraces 10 meters apart on intervention slopes.

Bracmort et al. (2004; 2006) studied the effects of long-term water quality impact of terraces taking into account varying conditions of terrace maintenance. They provide a detailed description of the procedure used to model a variety of SLWM terrace structures in SWAT. In addition, Arabi et al. (2007) test appropriate model parameters for representation of the effect of parallel terraces on runoff and soil moisture. Bearing in mind the hydrologic and water quality processes simulated in SWAT, the key parameters used to model terrace construction are SCS curve number (CN), USLE support practice factor (USLE_P), and slope length of the hillside (SLSUBBSN). Following Arabi et al. (2007), we decrease the curve number six units from its calibrated value to represent the reduction of surface runoff due to increased abstraction from small depressions created by terraces and bunds. We also decrease the slope length given that well-constructed terraces and bunds will break the original slope into a series of shorter slope distances, which will reduce the peak runoff rate. The SLSUBBSN represents the spacing between parallel terraces and bunds built along the contours of the agricultural fields. We modify SLSUBBSN for the terracing and bunds scenarios following field trials by Hurni (1985) and Herweg and Ludi (1999) in the highlands of Ethiopia(See Table 4).

Finally, the USLE_P was increased in order to represent level terracing for a variety of slope degrees and slope lengths. Gebremichael et al. (2005) reported calibrated USLE_P values for stone bunds from documented field experience and suggest that an average value of 0.32 is appropriate for the highland regions of Tigray, while Hurni (1985) recommended the P factor be adjusted to 0.5 to represent bunds investments throughout Ethiopia. We adjust the USLE_P parameters within defined bounds for each simulation (Table 4). We simulate terrace and bund investments given a variety of investment magnitudes including investing in terraces on only the steepest areas in the watershed (slopes of greater than 20 percent); terraces on slopes greater than 5 percent; and comprehensive terrace and bund investment whereby terraces are built in areas with greater than 5 percent slopes and bunds on areas with less than a 5 percent slope. Forested and urban areas are excluded from any intervention.

Table 4—Parameter changes for representation of SLWM investment scenarios in SWAT

Variable (function)	Base	Terraces[1]	Terraces [2]	Terraces [3]	Residue Mgt.[4]	Residue Mgt.[5]
CN2* **(Reduce overland flow)**						
0-5 slope	Base	Base	Base	-3.0	-2.0	Base
5-20 slope	Base	Base	-6.0	-6.0	-2.0	-2.0
>20 slope	Base	-6.0	-6.0	-6.0	-2.0	-6.0
USLE_P [6] **(Reduce sheet erosion)**						
0-5 slope	0.40	0.40	0.40	0.32	0.40	0.40
5-20 slope	0.45	0.45	0.32	0.32	0.45	0.45
>20 slope	0.75	0.50	0.50	0.50	0.75	0.75
SLSUBBSN **(Reduce slope length)**						
0-5 slope	50	50	50	30	50	50
5-20 slope	50	50	10	10	50	50
>20 slope	50	10	10	10	50	10
OV_N[7] **(Increase sediment capture / reduce overland flow)**	.15	.15	.15	.15	.19	.19

Source: Authors' calculations

*The base values vary based on hydrologic soil group, land use, antecedent moisture condition by HRU
[1]Terraces on steep terrain (slope > 20 degrees)
[2]Terraces on mid and steep terrain (slope >5 degrees)
[3]Terraces on mid and steep terrain and bund on 0-5 slope gradient
[4]Residue management on flat (< 5 degree slope) agricultural plots
[5]Residue management on agricultural plots 0-20 slope gradient and terraces on steep terrain
[6]Source: Betrie et al., 2011; Neitsch et al., 2005
[7] Source: Neitsch et al., 2005; Hurni, 1985

Residue management

Residue management is another low cost SLWM intervention. Leaving adequate residue on the ground after harvest and prior to tillage for planting will slow surface and peak runoff due to increased land cover and surface roughness; increase infiltration by slowing down overland flow; and reduce sheet and rill erosion by reducing surface flow volume and rate. In Ethiopia, however, mixed livestock and agricultural farming systems prevail, and, despite the low labor cost of residue management, there are important tradeoffs between SLWM activities and food and feed productions. Crop rotation is commonly practiced as a strategy for soil fertility management, but major constraints of increasing residue on agricultural plots are the need for fuel and feed (Tibebe and Bewket, 2011). Dung and crop residues are burned for fuel, while livestock are commonly left to feed on crop residue after the harvest, leaving no groundcover (Tadesse, 2001).

Research by Habtegebrial et al. (2007) analyzed minimum tillage practices in teff fields in the highlands of Ethiopia. Their results suggest that, on average, conventional tillage (leaving land bare for 2–3 months whereby fields are plowed 3 to 6 times prior to planting) provided 4.2 to 6.9 percent higher yields of dry matter and grain compared to the minimum tillage scenario. In addition Ashagre (2009) reported that farmers believed strongly in plowing their lands repetitively for a better teff yield and concluded that implementing a minimal or zero-tillage for fields growing teff is not realistic.

We model residue management assuming that a tillage operation occurs only prior to planting, and livestock grazing is limited, thus leaving residue on the fields after harvest, except for areas planted with teff. We evaluate residue management by estimating that 0.5 -1.0 mt per hectare of residue is conserved due to reduced tilling with residue left on the fields. The key parameters to adjust when modeling residue management include the curve number (CN2) and Manning's roughness coefficient for overland flow (OV N). The curve number is reduced by 2 units from the calibrated value in fields implementing residue management (Arabi et al., 2007). Neitsch (2005), based on Engman (1983) tested the OV N parameter for a variety of land surface characteristics and provide suggested values for a variety of land types. Manning's roughness coefficient for overland flow values are drawn from previous literature by Neitsch (2005) and Hurni (1985) in order to model residue management in Mizewa Watershed (See Table 4).

7. RESULTS

Simulations of the selected SLWM investments reported in this analysis suggest that improvements in infiltration, decreases in surface runoff, and decreases in erosion are achievable in the Mizewa watershed. The results of the daily SWAT simulations in the calibrated base scenario suggest that total streamflow ranged between 0.0 and 8.92 cubic meters per second (m^3/s). The average daily streamflow during the rainy season (June through September) in the baseline scenario was estimated at 0.68 m^3/s, while daily surface flow contributed 0.40 mm on average to overall water yields during the rainy season (Table 5 and Appendix Tables 3 and 4).

Table 5—Simulated average daily discharge during rainy season (June – September, 2009-2030)

Variable	Simulation	Mean	Min	Max
Total flow (m3/s)	Base (m3/s)	0.68	0	8.9
	Terrace (slope >20°)	0.62	0	8.3
	Terrace (slope >5°)	0.52	0	6.9
	Terrace (slope >5°) Bund (1-5 slope°)	0.52	0	6.8
	Residue management (< 5°) Terrace (>5°)	0.52	0	6.8
	Residue management (0-20° slope) Terrace (slope >20°)	0.61	0	7.9
Surface flow (mm)	Base	0.40	0	25.2
	Terrace (slope >20°)	0.40	0	25.2
	Terrace (slope >5°)	0.32	0	22.3
	Terrace (slope >5°) Bund (1-5 slope°)	0.25	0	20.5
	Residue management (< 5°) Terrace (>5°)	0.27	0	21.0
	Residue management (0-20° slope) Terrace (slope >20°)	0.32	0	22.9

Source: Authors' calculations

Note: Residue management assumes that 0.5 -1.0 mt per hectare of residue is conserved due to reduced tilling with residue left on the fields

Daily average total and surface flow decrease compared to the base in each investment simulation to varying degrees depending on the magnitude of the investment. The effectiveness of each simulation also depends on the share of land available and the topographical characteristics of the watershed. Given that 65 percent of the Mizewa watershed terrain has a slope between 5 and 20 degrees, the most effective SLWM investments on overall water balance measurements occur when investing on mid-range slopes, whereby average daily surface flow is reduced from 0.4 to 0.32 mm (20 percent) when constructing terraces in areas with greater than 5 degree gradients (Table 5). Similarly, a combination of residue management in flat and middle slope areas and terracing on steep slopes reduces surface runoff from 0.4 to 0.32 if practiced in mid-range sloped agricultural fields (Table 5). Finally, effects of extreme events on runoff response (maximum flow) also decrease with improved watershed management, although peak flows remain relatively high in all investment simulations.

Simulations suggest that a landscape-wide approach of terrace and bund construction has the greatest effect in terms of decreasing surface runoff and sediment yield. A comprehensive landscape investment of terraces on middle and steep slopes and soil bunds on slopes of 0-5 degrees over the simulation period (2009-2030) would decrease surface flow by approximately 47 percent, increase groundwater flow by 83 percent, and decrease sediment yield (erosion) by 92 percent (Table 6, Simulation 4). However, constructing only terraces in areas with greater than 5 percent slopes has a similar effect, whereby surface flow and sediment yield decreases by 43 and 90 percent respectively, and groundwater flow increases by 80 percent. Residue management also has a significant effect on surface flow and erosion in the Mizewa watershed. Average annual surface flow decreases by 29 percent when adopting steep terraces and residue management on flat and middle slope areas.

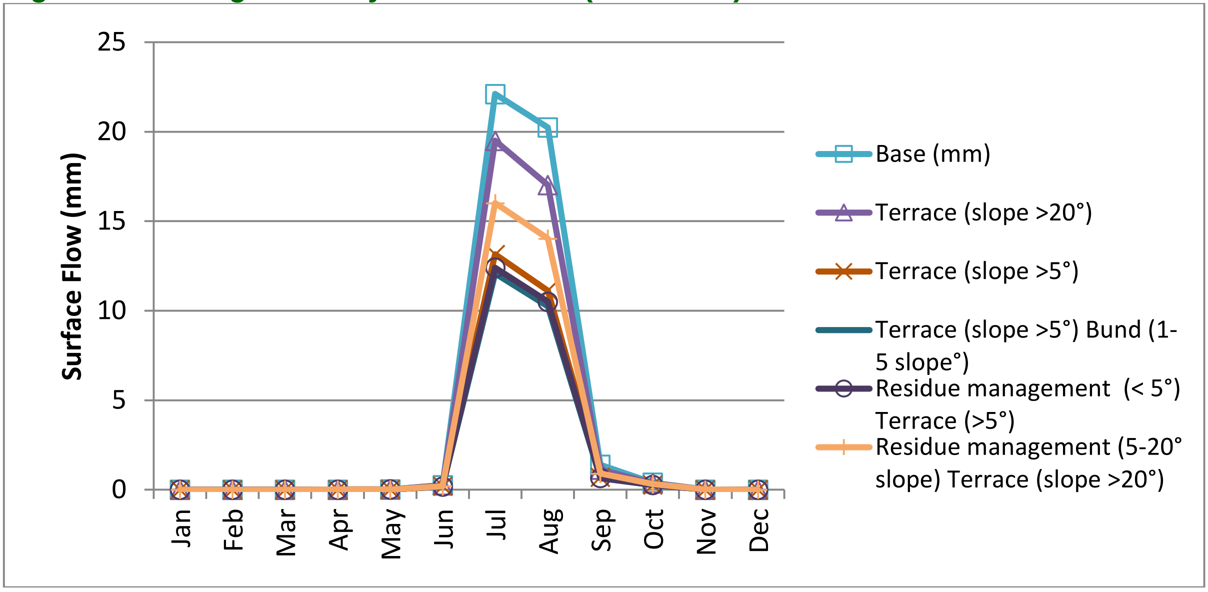
Table 6—Average annual simulated discharge and sedimentation of SLWM practices (2009-2030)

	Base (mm)	Terrace (slope >20°)	Terrace (slope >5°)	Terrace (>5° slope) Bund (1-5 slope°)	Residue mgt. (< 5° slope) Terrace (>5°)	Residue mgt. (<20° slope) Terrace (slope >20°)
Simulation	*1*	*2*	*3*	*4*	*5*	*6*
Surface flow	44.6	-13.8%	-42.6%	-47.2%	-45.8%	-29.1%
Groundwater flow	65.6	4.5%	80.4%	83.2%	82.3%	12.2%
Stream flow	313.0	-7.7%	-10.0%	-10.0%	-10.0%	-7.8%
Sediment Yield (mt/ha)	1.0	-35.4%	-90.3%	-92.2%	-88.7%	-45.5%

Source: Authors' calculations

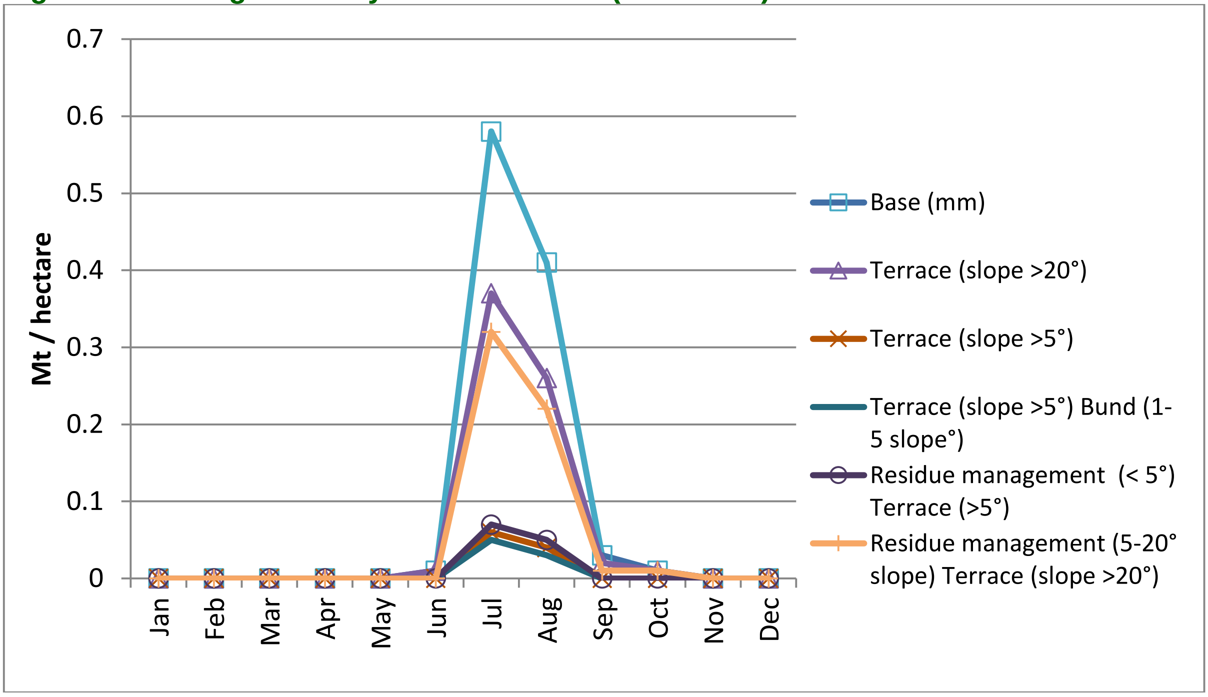
Simulations suggest that decreased average monthly runoff during the rainy season is the primary driver to reduce sediment yield and surface flow. In comparison to the base scenario, average surface flow during July (the peak month of the rainy season in Mizewa watershed) decreases from 22 mm in the base simulation to 13 mm in middle and steep terraces simulation (Figure 5). Similarly, sediment yields decrease in the month of July from 0.58 mt/hectare in the base to 0.06 mt/hectare in the month of July under the middle and steep terraces simulations (Figure 5 and 6). Residue management on flat and middle slopes with terraces on steep slopes has less of an effect on surface runoff and sediment. Surface flow is reduced from 22 mm (base simulation) to 16 mm in July and sediment yield / erosion decreased by 44 percent from 0.58 to 0.32 mt/ha in July.

Figure 5—Average Monthly Surface Flow (2009-2030)



Source: Authors' calculations

Figure 6—Average Monthly Sediment Yield (2009-2030)



Source: Authors' calculations

Due to decreased surface runoff and increased percolation into the shallow aquifer, groundwater flow is also increased as a result of SLWM investments. Simulated average monthly groundwater flow is not only greater in rainy months, but groundwater flow is prolonged into dry months as well (Table 6). Increased percolation may extend the crop growing period, which may have a direct effect on farmer livelihoods.

Caveats and areas for further study

Despite the breadth and depth of past analyses that have been modeled in SWAT, as well as the model's strength in modeling SLWM investments in agricultural watersheds, it is important to note model weaknesses. The uncertainty of input data is important to take into account given the short data collection period, as well as the nonlinear relationships between hydrologic input and response. Some of this ambiguity is addressed in sensitivity analyses[4] of the model parameters to identify the most sensitive parameters and their corresponding impact on model output. Spatial uncertainty of data capture is also an important consideration. For example, climatic variables and soil moisture data are averaged over the watershed area and may include measurement errors. Finally, the precipitation[5] and observed flow data (derived from stream level using a rating equation) were manually collected at 6am and 6pm daily, but in some cases did not capture large rain events occurring in the middle of the night[6]. The manual flow data were verified with three months of automatic flow station data which suggest a rapid time of concentration. In addition, we find that most mean observations from the manual data collection track well with the hourly automatic flow gauge data. The SWAT model relies on accurate precipitation data in order to predict runoff and infiltration from precipitation events, while reliable runoff data are needed for efficient calibration of the model.

In addition to model input uncertainty, Arabi et al. (2006, 2007) caution that the modeled impact of SLWM may be affected by the watershed subdivision routines used for parameterization of the watershed in SWAT. Analysis by Arabi et al. (2006) demonstrated that the estimated impact of SLWM significantly varied with the number of sub-watersheds. Additional analysis of appropriate watershed subdivision could provide greater insight to water balance effects of SLWM. Similarly, Nyssen et al. (2010) stress the need to recognize the biophysical differences (local differences in slope gradients, soil texture, vegetation and landcover, etc.) that define localized infiltration rates and impact of SLWM practices. The methods used to represent SLWM in the present study are based on historical and ongoing experimental trials of conservation practices and may not capture the unique processes that occur specifically in Mizewa watershed. Ongoing data collection and further research in the Mizewa watershed after SLWM interventions would allow for more in-depth analysis on specific impact of investments on water balance and discharge in the affected area.

Finally, the SLWM scenarios presented in this study are based on hydrologic processes represented in SWAT utilizing the SCS curve number method (SCS 1957). The SCS curve number method is widely used in mathematical representation of watershed models, and previous research in the Blue Nile Basin have sought out appropriate methods to simulating SLWM investments using the curve number approach. However, recent literature argues that the SWAT-Variable Source Area[7] (VSA) model, developed by White et al. (2010) and Easton et al. (2010) is a more appropriate framework for watersheds that experience monsoonal climates typical of the Ethiopian highlands. The primary difference between the SWAT-VSA and the original SWAT-Curve Number (CN) model is the method in which HRU's are classified. Similar to the SWAT-CN model, the SWAT-VSA model discerns between HRU's with the same land use and soil characteristics, but is designed to capture watershed areas dominated by variable source area (VSA) hydrology where topography is a major determinant of flow. Several studies have found a superior performance of the SWAT-VSA model compared to the CN model in the Ethiopian highlands (White et al. 2010; Tebebu et al. 2010; Collick et al. 2009; Steenhuis et al. 2009). However, there are no studies to date that test model parameter adjustments for SLWM investments on experimental plots or fields. Thus, it is unclear how to simulate future SLWM investments using SWAT-VSA. A future study could compare parameter modifications using the CN and the VSA model on pre- and post-investment data to assess appropriate value changes for modeling of specific SLWM structures (similar to work by Arabi et al. 2007 and Bracmort et al. 2006). Taking into account the spatial complexity of watershed-level management will provide a more comprehensive understanding of how these investments effect agricultural sustainability in the medium to long term.

8. CONCLUSION

Agricultural areas of the Blue Nile Basin continue to receive investments in SLWM infrastructure with the goal of enhancing agricultural productivity and household welfare in the highlands of Ethiopia. Earlier studies on

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[4] This analysis uses the method provided in ArcSWAT2005, which combines the Latin Hypercube (LH) and One-factor-At-a-Time (OAT) sampling (Van Griensven, 2005).

[5] An automatic, hourly precipitation gauge collected data at sub-watershed 1, and two manual precipitation gauges collected data at 6am and 6pm daily at sub-watershed 2 and 3 respectively.

[6] An hourly automatic flow gauge and a manual flow gauge were installed at the bridge. The automatic gauge was vandalized in December 2011 thus hourly data were only collected from August - December, 2011. The automatic gauge is currently being repaired.

[7] Surface runoff is produced by a small portion of a watershed that expands with an increasing amount of rainfall.

land degradation in the Blue Nile Basin suggest that land productivity decline is severe due to erosion and topsoil loss. Although basin-wide hydrological models have been used to analyze runoff and erosion in the Blue Nile Basin, micro-watershed analysis is lacking in Ethiopia due to limited data.

This analysis utilizes recent hydrological and meteorological data collected from the Mizewa watershed in order to better understand the physical impact of SLWM investments. The effectiveness of the simulated conservation practices (terraces, bunds, and residue management) are evaluated using the SWAT model taking into account investment decisions on different terrain types. Simulations include: 1) terracing on steep hillsides (slopes greater than 20 degrees); 2) terracing on mid-range and steep hillsides (slopes greater than 5 degrees); 3) a mix of terracing and bunds on varying slope gradients; 4) residue management on all agricultural fields; and 5) a mix of terraces and residue management on steep and mid-range terrain where a majority of agricultural activity takes place.

A comprehensive investment of terraces and bunds maintained throughout the watershed landscape provides the greatest reduction in surface flow and erosion. Results suggest that such an investment, if maintained over the simulation period (2009-2030) would decrease surface flow by almost 50 percent, increase groundwater flow by 15 percent, and decrease sediment yield by 85 percent. However, constructing only terraces in areas with a slope greater than 5 percent has a similar effect whereby surface flow and sediment yield decreases by 45 and 83 percent respectively, and groundwater flow increases by 13 percent. Given that the simulated investments decrease surface runoff, groundwater flow increases due to improvements in percolation. Increased percolation may extend the crop growing period, which may have a direct effect on farmer livelihoods.

The type and amount of investment in SLWM have different implications with respect to labor input and utilization of agricultural land. It is important to note that although simulations suggest that a landscape-wide approach may reap the greatest long-term benefits, it is important to understand the costs of such an investment. For example, terrace development requires the most labor input, including collection of stones, construction and maintenance of retaining walls over time. Residue management does not require high labor input, but incurs costs in terms of decreasing available livestock fodder given that grazing is reduced in order to maintain a sufficient amount of stubble and land cover on the fields.

Herweg and Ludi (1999) highlight important obstacles to farmer adoption including the tradeoff of SLWM structures occupying limited cropping area and that areas occupied by terraces or bunds are usually not weeded or ploughed and may attract rodents leading to field infestation. Schmidt and Tadesse (2012) estimated the costs of terrace and bund construction in selected woredas and found that net benefits of SLWM investments did not exceed costs. However, their analysis does not take into account a landscape investment approach, but rather an individual plot-level analysis. Hengsdijk et al. (2005) explored the tradeoffs of SLWM investments in Tigray region whereby bunds slightly increased crop productivity during drier periods when yields were low, but decreased productivity during moist seasons because overall cropped area was reduced for the construction of bunds. Similar to Schmidt and Tadesse (2012), Hengsdijk et al. (2005) evaluates individual plot and household level investments, rather than landscape or watershed level investments.

In order to explore policy options for incentivizing local investment and up-scaling of sustainable land management activities, it is important to understand the watershed system and the potential for improved hydrological performance at landscape and household level. This analysis provides the foundation for understanding feasible impacts of a more comprehensive, landscape SLWM investment strategy. Results stemming from this analysis could be paired with household level socio-economic data in order to assess program investment alternatives that take into account household constraints to SLWM investment and opportunity costs of SLWM maintenance on private and public land.

REFERENCES

Arabi, M., J.R. Frankenberger, B.A. Engel, and J.G. Arnold. 2007. Representation of agricultural conservation practices with SWAT. *Hydrological Processes.* 22(6): 3042-3055.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. *Journal of American Water Resources Association*. 34(1): 73-89.

Arnold, J.G., R.S. Muttiah, R. Srinivasan, and P. M. Allen. 2000. Regional estimation of base flow and groundwater recharge in the upper Mississippi basin. *Journal of Hydrology* 227(1-4): 21-40.

Arnold, J.G., J.R. Kiniry, R. Srinivasan, J.R. Williams, E.B. Haney, S.L. Neitsch. 2011. Soil and Water Assessment Tool Input/Output File Documentation Version 2009. Texas Water Resources Institute Technical Report No. 365.

Ashagre, Biniam Biruk. 2009. SWAT to identify watershed management options: (Anjeni Watershed, Blue Nile Basin, Ethiopia). MSc Thesis. Graduate School of Cornell University.

Acres, Meqaunint Tenaw and Seleshi B. Awulachew. 2010. SWAT based runoff and sediment yield modelling: a case study of the Gumera Watershed in the Blue Nile basin. *Ecohydrology and Hydrobiology*. 10(2-4): 191-200.

Betrie, G.D., Y.A. Mohamed, A. van Griensven, and R. Srinivasan. 2011. Sediment management modelling in the Blue Nile Basin using SWAT model*. Hydrology and Earth Systems Science*. 15: 807–818.

Bewket, Woldeamlak and Geert Sterk. 2005. Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia. *Hydrological Processes*. 19: 445-458.

Birhanu Zemadim, Matthew McCartney, and Bharat Sharma. 2012. Establishing Hydrological and Meteorological Monitoring Networks In Jeldu, Diga and Fogera Districts of the Blue Nile Basin, Ethiopia. Report Produced for CPWF Nile Project 2: Integrated rainwater management strategies – technologies, institutions and policies.

Blanco, Humberto and Lal, Rattan. 2008. Principles of Soil Conservation and Management. Springer Science+Business Media B.V.

Bosshart, U. 1997. Catchment Discharge and Suspended Sediment Transport as Indicators of Physical Soil and Water Conservation in the Minchet Catchment, Anjeni Research Unit, Soil Conservation Research Report 40, University of Berne, Berne, Switzerland.

Bracmort, K.S., B.A. Engel, and J.R. Frankenberger. 2004. Evaluation of structural best management practices 20 years after installation: Black Creek Watershed, IN. *Journal of Soil and Water Conservation* 59(5), 659-667.

Bracmort, K. S., M. Arabi, J.R. Frankenberger, B.A. Engel, and J.G. Arnold. 2006. Modeling Long-Term Water Quality Impact of Structural BMPs. *Transactions of the ASABE* 49(2), 367−374.

Chanasyk, D.S., E. Mapfumo, and W. Willms. 2003. Quantification and simulation of surface runoff from fescue grassland watersheds. *Agricultural Water Management* 59: 137-153.

Chandy, K.T. 2004. Bunding and Terracing. Booklet No. 593. Soil and Water Conservation: SWCS -11.

Collick, A.S., Z.M. Easton, E. Adgo, S.B. Awulachew, Z. Gete, and T.S. Steenhuis. 2009: Application of a physically-based water balance model on four watersheds throughout the upper Nile basin in Ethiopia. *Hydrological Processes* 23: 3718-3729.

Conway, D. 2000. The climate and hydrology of the Upper Blue Nile, Ethiopia. *Geographical Journal* 166, 49–62.

Deb, K. 2001. Multi-Objective Optimization using Evolutionary Algorithm. New York: John Wiley & Sons.

Desta Gebremichael, J. Poesen, J. Nyssen, J. Deckers, H. Mitiku, G. Govers, and J. Moeyersons. 2005. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray highlands, Northern Ethiopia. *Soil Use and Management*. 21: 287–297.

Descheemaeker, K., J. Nyssen, J. Rossi, J. Poesen, M. Haile, D. Raes, B. Muys, J. Moeyersons, and S. Deckers. 2006a. Sediment deposition and pedogenesis in exclosures in the Tigray Highlands, Ethiopia. *GEODERMA*. 132, 291–314, Descheemaeker K., J. Nyssen, J. Poesen, D. Raes, M. Haile, B. Muys, S. Deckers. 2006b. Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia. *Journal of Hydrology* 331: 219-241.

Descheemaeker K., J. Poesen, L. Borselli, J. Nyssen, D. Raes, M. Haile, B. Muys, and J. Deckers. 2008. Runoff curve numbers for steep hillslopes with natural vegetation in semi-arid tropical highlands, northern Ethiopia*. Hydrological Processes* 22: 4097-4105.

Easton, Z.M., D.R. Fuka, M.T. Walter, D.M. Cowan, E.M. Schneiderman, and T.S. Steenhuis. 2008. Re-conceptualizing the Soil and Water Assessment Tool (SWAT) model to predict runoff from variable source areas. *Journal of Hydrology*. 348(3-4), 279-291.

Eldaw, A.K., J.D., Salas and L.A. Garcia. 2003. Long-range forecasting of the Nile river flows using climatic forcing. *Journal of Applied Meteorology.* 42, 890–904.

Engman, E.T. 1983. Roughness coefficients for routing surface runoff. Proc. Spec. Conf. Frontiers of Hydraulic Engineering.

Eweg H and R. Van Lammeren. 1996. The application of a geographical information system to the rehabilitation of degraded and degrading areas. A case study in the highlands of Tigray, Ethiopia. Centre for Geographical Information Processing, Agricultural University of Wageningen.

Gebremichael, D., J. Nyssen, J. Poesen, J. Deckers, M. Haile, G. Govers and J. Moeyersons. 2005. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray highlands, Northern Ethiopia, *Soil Use and Management*, 21, 287–297.

Habtegebrial, K., B.R. Singh, M. Haile. 2007. Impact of tillage and nitrogen fertilization on yield, nitrogen use efficiency of teff (Eragrostis tef (Zucc.) Trotter) and soil properties. *Soil & Tillage Research* 94 : 55–63.

Haileslassie, A., F. Hagos, E. Mapedza, C. Sadoff, S.B. Awulachew, S. Gebresellasie, and D. Peden. 2008. Institutional settings and livelihood strategies in the Blue Nile Basin: implications for upstream/downstream linkages. International Water Management Institute (IWMI) Working Paper 132. Addis Ababa, Ethiopia.

Hengsdijk, H, G.W. Meijerink, and M.E. Mosugu. 2005. Modeling the effect of three soil and water conservation practices in Tigray, Ethiopia. *Agriculture, Ecosystems and Environment* 105, 29–40.

Herweg, K. and E. Ludi.1999. The Performance of Selected Soil and Water Conservation Measures-case Studies from Ethiopia and Eritrea. *Catena*. 1-2: 99-114.

Holden, ST, H. Lofgren, B. Shiferaw. 2005. Economic Reforms and Soil Degradation in the Ethiopian Highlands: A Micro CGE Model with Transaction Costs. Paper presented at the ECOMOD conference, Istanbul.

Holden, S. T. and B. Shiferaw. 2002. Poverty and Land Degradation: Peasants' Willingness to Pay to Sustain Land Productivity. In C. B. Barrett, F. M. Place, and A. A. Aboud (eds.), *Natural Resource Management in African Agriculture: Understanding and Improving Current Practices*. CABI Publishing in Association with International Centre for Research in Agroforestry, Oxon and New York.

Holden, S.T., K. Deininger, and H. Ghebru. 2009. Impacts of Low-Cost Land Certification on Investment and Productivity. *American Journal of Agricultural Economics.* 91(2), 359–373.

Hurni, H., S. Abate, A. Bantider, B. Debele, E. Ludi, B. Portner, B. Yitaferu, G. Zeleke. 2010. Land Degradation and Sustainable Land Management in the Highlands of Ethiopia. In Hurni, H. and U. Wiesmann (eds.) (2009) *Global Change and Sustainable Development: A Synthesis of Regional Experiences from Research Partnerships*. University of Bern, Geographica Bernensia, Perspectives of the Swiss National Centre of Competence in Research (NCCR) North-South Vol. 5. Bern, CDE. 187 – 207.

Hurni, H. 1985. Erosion – productivity – conservation systems in Ethiopia, in Proceedings of the 4th International Conference on Soil Conservation, Maracay, Venezuela, 654–674.

Kalin L. and M.M. Hantush. 2003. Evaluation of sediment transport models and comparative application of two watershed models. EPA/600/R-03/139, National Risk Management Research Laboratory, Office of Research and Development. U.S. Environmental Protection Agency, Cincinnati, OH 45268.

Kassie, M., J. Pender, M. Yesuf, G. Kohlin, R. Bluffstone, and E. Mulugetu. 2007. Impact of soil conservation on crop production in the Northern Ethiopian Highlands, IFPRI Discussion Paper 00733. Washington, DC: International Food Policy Research Institute (IFPRI).

Kim, U., J.J. Kaluarachchi, and V.U. Smakhtin. 2008. Climate Change Impacts on Hydrology and Water Resources of the Upper Blue Nile River Basin, Ethiopia. International Water Management Institute (IWMI) Research Report 126. Colombo, Sri Lanka.

Legesse, D., C. Vallet-Coulomba, F. Gassea. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology* 275: 67-85.

Liu, B. M., A.S. Collick, G. Zeleke, E. Adgo, Z.M. Easton and T.S. Steenhuis. 2008. Rainfall-discharge relationships for a monsoonal climate in the Ethiopian highlands. Hydrological Processes. 22: 1059–1067. doi: 10.1002/hyp.7022

Ministry of Water and Energy. Bahir Dar daily precipitation data 1961 – 2011. Federal Democratic Republic of Ethiopia. Downloaded October 2012.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers* 50: 885–900.

Nash, J. E. and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models Part 1 – A discussion of principles*. Journal of Hydrology*. 10(3):282–290.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams, 2005: Soil and Water Assessment Tool Theoretical Documentation, Version 2005. Temple, Tex.: USDA-ARS Grassland, Soil and Water Research Laboratory.

———, 2002: Soil and Water Assessment Tool – User's Manual. Version 2000. Blackland Research & Extension Center, Temple, Texas, USA.

———, 2001: Soil and Water Assessment Tool Theoretical Documentation, Version 2000. Temple, Tex.: USDA-ARS Grassland, Soil and Water Research Laboratory.

Nyssen, J., J. Poesen, M. Veyret-Picot, J. Moeyersons, M. Haile, J. Deckers, J. Dewit, J. Naudts, K. Teka, G. Govers. 2006. Assessment of gully erosion rates through interviews and measurements: a case study from Northern Ethiopia. *Earth Surface Processes and Landforms* 31: 167-185.

Nyssen J., J. Poesen, D. Gebremichael, K. Vancampenhout, M. D'Aes, G. Yihdego, G. Govers, H. Leirs, J. Moeyersons, J. Naudts, N. Haregeweyn, M. Haile, J. Deckers. 2007. Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. *Soil and Tillage Research* 94: 151-163.

Nyssen, J., W. Clymans, K. Descheemaeker, J. Poesen, I. Vandecasteele, M. Vanmaercke, A. Zenebe, M. Van Camp, M. Haile, N. Haregeweyn, J. Moeyersons, K. Martens, T. Gebreyohannes, J. Deckers, K. Walraevens. 2010. Impact of soil and water conservation measures on catchment hydrological response—a case in north Ethiopia. *Hydrological Processes*. 24(13): 1880–1895.

Pender, J., and B. Gebremedhin. 2006. Land management, crop production and household income in the highlands of Tigray, Northern Ethiopia: An econometric analysis, in Pender, J., F. Place, and S. Ehui (eds.) *Strategies for sustainable land management in the East African Highlands*, Washington, DC: International Food Policy Research Institute.

Santhi, C, J. G. Arnold, J. R. Williams, W. A. Dugas, R. Srinivasan, and L. M. Hauck. 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. *Journal of American Water Resources Association*. 37(5): 1169-1188.

Santhi, C, J. R. Srinivasan, J.G. Arnold, J.R. Williams. 2006. A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. *Environmental Modelling & Software.* 21: 1141-1157.

Schmidt, E. and P. Dorosh. 2009. A Sub-National Hunger Index for Ethiopia: Assessing Progress in Region-Level Outcomes. Ethiopia Strategy Support Program-2 Working Paper #5. IFPRI – ESSP2. Addis Ababa, Ethiopia.

Shiferaw, B., and T.S. Holden. 1998: Resource Degradation and Adoption of Land Conservation Technologies in the Highlands of Ethiopia: A Case Study of Andit Tid, North-Shewa, *Agricultural Economics* 21, 53–67.

———.2001. Farm-level benefits to investments for mitigating land degradation: Empirical evidence for Ethiopia*, Environment and Development Economics* 6: 336–359.

Soil Conservation Service. 1957. Use of Storm and Watershed Characteristics in Synthetic Hydrograph Analysis and application. U.S. Department of Agriculture. Washington, D.C.

Steenhuis, T.S., A.S. Collick, Z.M. Easton, E.S. Leggesse, H.K. Bayabil, E.D. White, S.B. Awulachew, E. Adgo and A. Abdalla-Ahmed. 2009. Predicting discharge and erosion for the Abay (Blue Nile) with a simple model. *Hydrological Processes* 23: 3728-3737.

SWAT. The Global Weather Data for SWAT database. Temperature (C); Wind (m/s); Relative Humidity (fraction); and Solar (MJ/m^2). Dates of data: 1/1/1990 - 12/31/2010. Weather data requested on 3/25/2013 10:11 AM

Taddese, Girma. 2001. Land Degradation: A Challenge to Ethiopia. *Environmental Management* 27(6): 815–824

Taffese, Tewodros. 2012. Physically based rainfall – runoff modeling in the Northern Ethiopia Highlands: The case of Mizewa watershed. MSc. Thesis: Bahir Dar University. Water Resource Engineering Institute of Technology.

Tesfahunegn, G.B., L. Tamene, P.L.G. Vlek. 2011. Evaluation of soil quality identified by local farmers in Mai-Negus catchment, northern Ethiopia. *Geoderma.* 163(3):209-218.

Tibebe, D. and W. Bewket. 2011. Surface runoff and soil erosion estimation using the SWAT model in the Keleta watershed, Ethiopia. *Land Degradation & Development*. 22: 551–564.

Tripathi M.P. and N.S. Raghuwanshi. 2003. Identification and prioritization of critical sub-watersheds for soil conservation management using the SWAT model. *Biosystems Engineering* 85: 365–379.

Ungtae, Kim and J.J. Kaluarachchi. 2008. Application of parameter estimation and regionalization methodologies to ungauged basins of the Upper Blue Nile River Basin, Ethiopia. *Journal of Hydrology*. 362: 39–56

Van Griensven, A. 2005. Sensitivity, auto-calibration, uncertainty and model evaluation in SWAT2005. Unpublish report. http://biomath.ugent.be/~ann/swat_manuals/SWAT2005_manual_sens_cal_unc.pdf

Van Liew, M.W., J.G. Arnold, and J.D. Garbrecht. 2003. Hydrologic simulation on agricultural watersheds: Choosing between two models. *Transactions of the American Society of Agricultural Engineers*. 46(6): 1539-1551.

Van Liew, M.W. T.L. Veith, D.D. Bosch, and J.G. Arnold. 2007. Suitability of SWAT for the Conservation Effects Assessment Project: Comparison on USDA Agricultural Research Service Watersheds. Publications from USDA-ARS / UNL Faculty. Paper 473

Werner, C. 1986. Soil conservation experiments in Anjeni, Gojam Research Unit, Ethiopia.

White, E.D., Z.M. Easton, D.R. Fuka, A.S. Collick, E. Adgo, M. McCartney, S.B. Awulachew, Y.G. Selassie and T.S. Steenhuis, 2011: Development and application of a physically based landscape water balance in the SWAT model. *Hydrological Processes* 25, 915-925.

Williams, J. R. 1995. The EPIC model. In V. P. Singh (ed). *Computer Models of Watershed Hydrology*, 909-1000. Highlands Ranch, Colo.: Water Resources Publications.

Wischmeier, W.H. and Smith, D.D. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains - Guide for selection of practices for soil and water conservation. Agricultural Handbook No. 282.

———.1978. Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Agriculture Handbook No. 537. USDA/Science and Education Administration, US. Govt. Printing Office, Washington, DC. 58pp

Yates, D., and K. Strzepek. 1998. Modeling the Nile Basin under climatic change. *Journal of Hydrological Engineering* 3(2), 98 – 108.

Yesuf, M, A. Mekonnen, M. Kassie, J. Pender. 2005. Cost of Land Degradation in Ethiopia: A Critical review of Past Studies. Addis Ababa, Ethiopia: EDRI/EEPFE.

Yesuf, M. and R. A. Bluffstone. 2008. Wealth and Time Preference in Ethiopia. Environment for Development EfD Discussion Paper 08-16. Addis Ababa, Ethiopia: EEPFE/EDRI

Yitbarek, T.W., S. Belliethathan, L.C. Stringer. 2010. The onsite cost of gully erosion and cost-benefit of gully rehabilitation: A case study in Ethiopia, *Land Degradation and Development.* 23(2), 157–166.

Zeleke, G., and H. Hurni. 2001. Implications of land use and land cover dynamics for mountain resource degradation in the Northwestern Ethiopian highlands, *Mountain Research and Development.* 21(2), 184–191.

Zemadim, B., M. McCartney, and B. Sharma. 2012. Establishing hydrological and meteorological monitoring networks in Jeldu, Diga and Fogera districts of the Blue Nile Basin, Ethiopia. Report Produced for CPWF Nile Project 2: Integrated rainwater management strategies – technologies, institutions and policies.

APPENDICES

Appendix Table 1: Details of data network in Mizewa watershed, Fogera woreda

Location name	Gauge type	Location	Elevation (masl)	Land use, land cover
Water level gauges				
Mizewa road bridge	Automatic and manual	11°56.174'N; 37°47.154'E	1,862-2,391	-
Mizewa river upstream of confluence	Manual	11°55.765' N; 37°47.539'E	1,875-2,391	-
Zinjero Gedel river upstream of confluence	Manual	11°55.741'N; 37°47.538'E	1,872-2,290	-
Soil moisture probe and groundwater monitoring device				
SM Mizewa 1	Automatic	11°54'55''.7N; 37°47'11''.5 E	1,941	Sloped grassland, short vegetation and eucalyptus
SM Mizewa 2	Automatic	11°54'58''.4N; 37°47'13''.8 E	1,922	Farmland
SM Mizewa 3	Automatic	11°55'00''.3 N; 37°47'21''.7 E	1,908	Short grass Non-grazing land
SM Mizewa 6	Automatic	11°54'35''.4 N; 37°47'19''.4 E	1,938	Short grass near farm area
SM Mizewa 8	Automatic	11°54'48''.7 N; 37°47'24''.3 E	1,927	Niger oil farm with stream boundary and trees
SM Mizewa 9	Automatic	11°54'50''.6 N; 37°47'26''.6E	1,922	Grassland with farmland boundary
Precipitation and climate monitoring stations				
Awramba primary school*	Automatic	11°55'00.6''N 37°47'18.0''E	1,903	-
Jigudguad	Manual	11°55'06''.6N 37°48'44.1''E	1,836	-
Timinda	Manual	11°55'06.6''N 37°48'44.1''E	1,946	-

* Includes gauges for humidity, air temperature, wind speed and direction, solar and net radiation, soil temperature and air pressure, as well as a precipitation gauge.

Appendix Table 2: Crop calendar used in the Anjeni watershed

	Growing season		Harvesting season		Plowing season	
Crop	**Start**	**End**	**Start**	**End**	**Start**	**End**
Barley	23-May	5-Sep	5-Sep	9-Dec	9-Apr	23-May
Teff	27-Jul	19-Dec	19-Dec	9-Mar	7-Feb	27-Jul
Wheat	6-Aug	30-Dec	30-Dec	7-Feb	7-Feb	6-Aug
Maize	23-May	9-Dec	9-Dec	9-Dec	18-Feb	9-May
Soy Bean	6-Aug	9-Dec	9-Dec	8-Jan	8-Jun	6-Aug

Source: Ashagre, 2009.

Appendix Table 3: Average Monthly Total Flow (mm) (2009-2030)

Month	Base	Terraces[1]	Terraces[2]	Terraces[3]	Residue Mgt.[4]	Residue Mgt.[5]
Jan	4.66	4.68	10.7	10.86	10.81	5.12
Feb	1.94	1.93	4.8	4.97	4.9	2.18
Mar	0.83	0.76	1.39	1.51	1.47	0.85
Apr	1.18	1.01	0.77	0.77	0.77	1.01
May	1.54	1.32	0.99	0.99	0.99	1.32
Jun	8.96	7.77	5.9	5.88	5.89	7.73
Jul	101.16	90.35	68.51	67.52	67.83	87.46
Aug	115.47	104.4	87.2	86.66	86.83	102.88
Sep	38.2	36.69	41.02	41.27	41.21	37.64
Oct	17.46	17.91	25.92	26.2	26.12	18.75
Nov	12.3	12.82	19.58	19.8	19.74	13.53
Dec	8.61	8.82	14.71	14.92	14.86	9.46

Source: Authors' Calculation

Notes: [1] Terraces on steep terrain (slope > 20 gradient).

[2] Terraces on mid and steep terrain (slope > 5 gradient).

[3] Terraces on mid and steep terrain and bund on 0–5 slope gradient.

[4] Residue management on flat agricultural plots and terraces on greater than 5 degree slopes.

[5] Residue management on agricultural plots 0–20 slope gradient and terraces on steep terrain (>20 degree slope).

Appendix Table 4: Average Monthly Surface Flow (mm) (2009-2030)

Month	Base	Terraces[1]	Terraces[2]	Terraces[3]	Residue Mgt.[4]	Residue Mgt.[5]
Jan	0	0	0	0	0	0
Feb	0	0	0	0	0	0
Mar	0	0	0	0	0	0
Apr	0.01	0.01	0.01	0.01	0.01	0.01
May	0.02	0.02	0.02	0.02	0.02	0.02
Jun	0.26	0.25	0.2	0.18	0.18	0.2
Jul	22.11	19.5	13.15	12.08	12.41	16.01
Aug	20.24	17.02	11.12	10.24	10.51	14.03
Sep	1.4	1.13	0.71	0.64	0.66	0.9
Oct	0.39	0.36	0.28	0.26	0.27	0.31
Nov	0.01	0.01	0.01	0.01	0.01	0.01
Dec	0	0	0	0	0	0

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The Ethiopia Strategy Support Program II is an initiative to strengthen evidence-based policymaking in Ethiopia in the areas of rural and agricultural development. Facilitated by the International Food Policy Research Institute (IFPRI), ESSP II works closely with the government of Ethiopia, the Ethiopian Development Research Institute (EDRI), and other development partners to provide information relevant for the design and implementation of Ethiopia's agricultural and rural development strategies. For more information, see http://www.ifpri.org/book-757/ourwork/program/ethiopia-strategy-support-program or http://essp.ifpri.info/ or http://www.edri-eth.org/.

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