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Hydrological modelling of sustainable land management interventions in the Mizewa watershed of the Blue Nile basin

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Abstract: The current paper discusses the use of hydrological modelling tool to understand sustainable land management interventions in the Blue Nile basin of Ethiopia. A micro-watershed named Mizewa with a drainage area of 27 km^2 in Fogera district was selected and instrumented with hydrological cycle observation networks in the year 2011. The SWAT hydrological modelling tool was used to simulate landscape-wide Soil and Water Conservation (SWC) investments. Simulations of the selected investments modelled in this analysis suggest that improvements in infiltration, decreases in surface runoff and decreases in erosion are achievable in the watershed. Further simulations suggest that a landscape-wide approach of terrace and bund construction has the greatest effect in terms of decreasing surface runoff, decreasing sediment yield and increasing groundwater flow and shallow aquifer recharge. A comprehensive landscape investment of terraces on slopes greater than 5% and bunds maintained on slopes less than 5% would decrease surface flow by almost 50%, increase groundwater flow by 15% and decrease sediment yield from erosion by 85%. However, constructing terraces in areas with greater than 5% slope (without constructing bunds in areas under 5% slopes) has a similar effect whereby surface flow and sediment yield decreases by 45 and 83%, respectively and groundwater flow increases by 13%. Residue management also has a significant effect on surface flow and erosion in the Mizewa watershed. Average annual surface flow decreased 17 when adopting residue management on all agricultural land and 26% when coupling terracing on steep slopes with residue management in mid-range slopes. These analyses provide the foundation for understanding feasible outcomes given a more comprehensive investment strategy. Results stemming from the current work can be paired with household level socio-economic data in order to assess program investment alternatives taking into account household constraints to Sustainable Land and Watershed Management (SLWM) investment and maintenance on private and public lands.

Media grab: Hydrological modelling techniques can support decision-makings for Sustainable Land and Watershed Management (SLWM)

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 fresh water 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, water scarcity and low water tables cause previously perennial streams to be intermittent and may affect agricultural yields in the Upper Blue Nile basin.

The Blue Nile is one of the least planned and managed subbasins of the Nile (IWMI 2008). Previous studies have examined the impact of investments in sustainable land and watershed management (SLWM) derived implicitly from economic analyses (Pender and Gebremedhin 2006; Schmidt and Tadesse 2012), but the physical improvements of SLWM investments (i.e. decreased surface runoff and sediment yield and increased groundwater flow during the dry season) require further examination through a hydrological model which takes into account comprehensive landscape investments and their effect on overall water balance. This analysis focuses on the impact of a variety of SLWM investments on runoff and sediment capture and seepage within the Mizewa watershed in Fogera district.

The study utilizes recent hydrological and meteorological data (stream flow, rainfall, weather and groundwater measurements) collected from the previously ungauged Mizewa watershed in order to understand more localized impacts of sustainable land management practices. The Soil and Water Assessment Tool (SWAT) (developed by the US Department of Agriculture; Arnold et al. 1998) is utilized to simulate sediment and runoff processes in order to better understand the physical impact (in terms of hydrological processes and linkages to agricultural yields) of SLWM investments.

Simulated conservation practices are evaluated at the outlet of Mizewa watershed by comparing model simulations with the limited investments that currently exist (status quo) with simulations of a variety of terracing and residue management activities. Results suggest that parallel terrace and bund construction significantly reduced surface runoff and sediment yield and improved groundwater flow. 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 mid-range slopes decreased surface runoff and sediment yield by 26 and 54%, respectively.

Methods

Study area description and model input data

The Mizewa watershed is situated in Fogera district located in the northeast of the Blue Nile basin near Lake Tana (Figure 1). The watershed modelled in this study encompasses the Mizewa River and is approximately 27 km^2, with the highest point in the catchment reaching 2391 masl.

This study uses data from recently installed gage stations in the previously ungauged Mizewa watershed in order to understand more localized impacts of sustainable land management practices on runoff and erosion. From June through August of 2011, a network of data gages were installed in the Mizewa watershed including: soil moisture probes, automatic and manual water level gauges, a weather station, manual rain gauges and shallow ground water monitoring devices. The climate monitoring data used in this analysis consists of one automatic weather station and two manual rain gages.

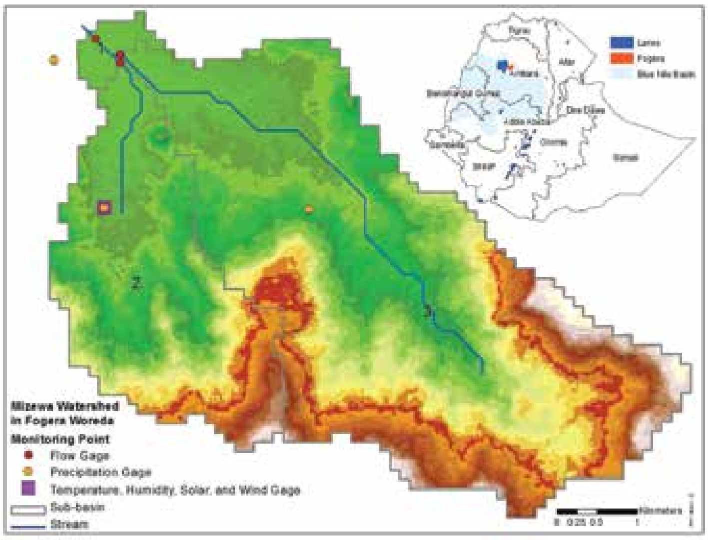

Figure 1. Mizewa watershed, elevation and streambed

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 (January 2009–2011) period utilized long-term weather data from 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. Calibration and verification were performed on the simulation period ranging from November 2011 to November 2012. Several statistics including the Nash-Sutcliffe prediction efficiency (ENS), coefficient of determination (R^2), Index of Volumetric Fit (IVF) and graphical plot were used to compare model predictions against the observed values. The model is calibrated at a daily, weekly and monthly time step. Surface and base flow were calibrated simultaneously. Simulated results suggest that temporal dynamics are important in the overall hydrologic behaviour 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 exception to the first event whereby the model anticipates time to concentration the first week of July, which results in a lower overall ENS and R^2 value (Table 1, Figure 2). 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 1. Nash Sutcliffe Coefficient and R^2 for calibration and validation of outlet discharge

	Calibration			Validation		
	ENS	R2	IVF	ENS	R2	IVF
Daily	0.39	0.41	99.3	0.24	0.27	74.09
Weekly	0.72	0.73	99.04	0.61	0.69	73.96
Monthly	0.93	0.94	99.35	0.71	0.81	74.09

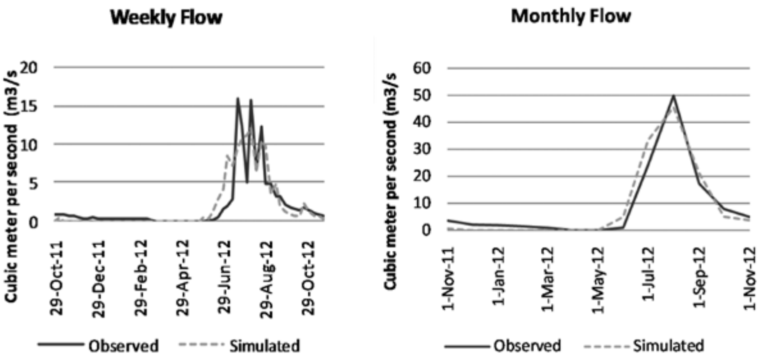

Figure 2. Calibration comparisons between observed and simulated weekly and monthly stream flow

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 ENS and R^2 to test model validity (Table 1, Figure 3).

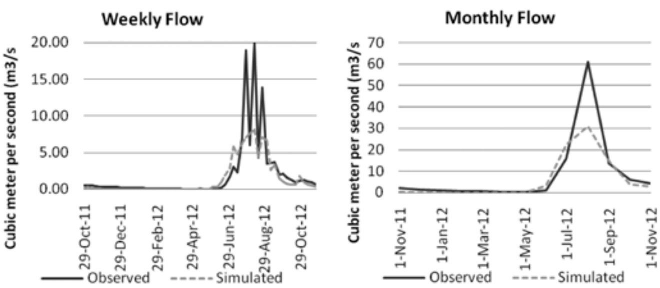

Figure 3. Validation comparisons between observed and simulated weekly and monthly stream flow

Simulating SLWM investments

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 National Meteorological Agency from 1961 to 2011 in order to simulate the effects of SLWM investments. The Global Weather Data for SWAT database supplied data for the other long-term weather input variables (air temperature and solar radiation, wind speed and relative humidity) required for SWAT simulation based satellite data and reported weather data from Bahir Dar and Addis Zemen weather stations.

In the study terraces are modelled under three scenarios: 1) terraces built on only steep land (greater than 20 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 labour investments, residue management is another strategy that is less labour intensive, but requires grazing limitations on agricultural land. We simulated residue management under two scenarios: 1) assuming that 0.5–1 ton/ha residue is left on all agricultural fields between harvest and planting seasons and 2) assuming that 0.5–1 ton/ha residue is left on agricultural fields with a mid-range slope, while steeper slopes (greater than 20 degree gradient) receive terraces. Although contour farming is often modelled 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. 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). The key parameters to adjust when modelling residue management are the curve number (CN2) and Manning's roughness coefficient for overland flow (OV N).

Results and discussions

Simulations of the selected SLWM investments modelled in this analysis suggest that improvements in infiltration, decreases in surface runoff and decreases in erosion is achievable in the Mizewa watershed. Daily average total flow and surface flow decrease compared to the base in each investment scenario, though to varying degrees depending on the magnitude of the investment. Table 2 presents effects of investments on different components of the hydrological cycle.

Table 2. Average annual simulated discharge and sedimentation under different SLWM practices

	Base (mm)	Terrace (slope >20°)	Terrace (slope >5°)	Terrace (slope >5°) Bund (1–5 slope°)	Residue management	Residue management (5–20° slope) Terrace (slope >20°)
Surface flow	45.0	–15.2%	–45.1%	–49.6%	–17.3%	–25.9%
Lateral flow	200.3	1.4%	2.9%	3.0%	0.9%	2.0%
Groundwater flow	72.2	0.0%	13.0%	15.4%	6.2%	4.7%
Stream flow	317.6	–1.2%	–1.6%	–1.7%	–0.5%	–1.4%
Sediment Yield	1.99	–45.4%	–82.5%	–85.0%	–19.2%	–53.9%

Simulations suggest that average monthly runoff during the rainy season is the primary driver to decreased sediment yield and surface flow, as well as increased and prolonged groundwater flow during the dry season. In comparison to the base scenario, surface flow during July (the peak month of the rainy season in Mizewa watershed) decreases from 26 mm to 16.8 mm under the mixed terrace and residue management simulation. Similarly, sediment yields decrease from 1.03 t/hectare in the base scenario to 0.47 t/hectare in the month of July under the mixed terrace and residue management simulation (Table 2). Terracing on greater than 5% slopes and the mixed terracing and bunds simulations suggest similar outcomes, whereby surface flow is reduced by 45 50% (12.4 and 11.3 mm), respectively in July and sediment yield decreased by 82 and 85% (0.17 and 0.15 t/ha).

Conclusions and recommendations

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.

The SLWM scenarios presented in this study are based on hydrologic processes represented in SWAT utilizing the SCS curve number method. Recent literature argues that the SWAT-Variable Source Area (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. However there are no studies to date that test model parameter adjustments for SLWM investments on experimental plots or fields apart from the conventional SCS curve number method. 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 modelling of specific SLWM structures taking into account the spatial complexity of watershed-level management will provide a more comprehensive understanding of how these investments affect agricultural sustainability in the medium to long term.

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 a landscape and household level scale. Future analysis would benefit from coupling household level investment choices with more comprehensive landscape wide interventions in order to take into account wider biophysical impacts, as well as household level economic factors. Successful past programs have supported a participatory planning approach that takes into account the relationships between household/village opportunity costs, perceived risk and changing social and economic dynamics. This analysis provides the foundation for understanding feasible outcomes given a more comprehensive investment strategy. Results stemming from this analysis can now be paired with household level socio-economic data in order to assess program investment alternatives taking into account household constraints to SLWM investment and maintenance on private and public land.

Acknowledgements

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