Using SWAT model to evaluate the impact of community-based soil and water conservation interventions for an Ethiopian watershed

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Abstract

Extensive land degradation in the Ethiopian highlands forces the rural communities to prevent further soil erosion to ensure sustainable land management in the endangered regions. Soil conservation measures are continuously being established in some areas by research and/or development projects but the effects at field and watershed level are unclear.
The objective of this study is to model runoff and sediment yield in the Gumara-Maksegnit watershed in the northern Amhara region, to assess the impact of selected soil and water conservation interventions. SWAT was used to simulate the 54 km² large watershed, locally treated by stone bunds and water retention ponds, based on SRTM-DEM data, soil data derived from 234 observations, a land-use map based on supervised satellite-image classification and weather data from four different rain gauges. Runoff and sediment concentration was monitored at three gauging stations to provide a reliable model calibration. Comprehensive field monitoring was undertaken to assess upland and channel processes and thus to consolidate the model performance. By means of the calibrated model mean annual runoff (271 mm) and soil loss (22.6 t ha^{-1}) was calculated and the highly endangered regions concerning land degradation were located. The achieved NSE of modeled and observed daily runoff of 0.777 indicates that the SWAT model can be properly used for the assessment of the on-site watershed characteristics and based on this, various scenarios can be simulated to identify efficient soil conservation strategies for the study area.

Keywords: Soil conservation, gully erosion, Ethiopian highlands, sediment concentration.

Introduction

In Ethiopia, soil erosion by water contributes significantly to food insecurity and constitutes a serious threat to sustainability of the existing subsistence agriculture (Hurni, 1993; Sutcliffe, 1993; Sonneveld, 2002). FAO (1984) and Hurni (1993) estimated that in the Ethiopian highlands annual soil loss reaches up to 200 to 300 tons per hectare.

The extensive famine of 1973 and 1974 initiated a first governmental rethinking concerning rural land management and consequently large-scale soil conservation and rehabilitation programs were undertaken (Hurni, 1985). Kruger et al. (1996) reported that between 1975 and 1989, 980000 hectares of cropland were protected by terraces and 310000 hectares of denuded lands were re-vegetated in highly degraded areas. However, the achievements of several soil conservation projects remained below the expectations and considerable efforts in soil conservation failed to prevent ongoing land degradation.

In the Gumara-Maksegnit watershed in the Ethiopian highlands a study was carried out to 1.) localize the hot-spots of surface runoff and soil erosion and 2.) to evaluate the effects of different soil conservation techniques. SWAT was used to model the 54 km² large watershed, locally treated by soil conservation measures, to be used as a basis for future watershed planning to combine agricultural and socio-economic demands with soil conservation requirements according to the spatially variable conditions of this region.

Materials and Methods

Study area

The Gumara-Maksegnit watershed is located in the Lake Tana basin in the northwestern Amhara region, Ethiopia between 12° 24’ and 12° 31’ North and between 37° 33’ and 37° 37’ East. The 54 km² large watershed drains into the Gumara River, which ultimately reaches Lake Tana. The climate in the northwestern Amhara region is characterized by heavy rainfall events during the rainy season from May to October and a dry spell from November to April. Mean annual rainfall is about 1170 mm at which more than 90 % of the rainfall occurs during the rainy season. The average monthly maximum and minimum temperatures are 28.5°C respectively 13.6°C. The elevation of the watershed ranges from 1920 m to 2860 m above sea level.

In the watershed five different soil types were determined: sandy clay loam, sandy loam, clay loam, loam, and clay. Shallow loam soils (rooting depth < 15 cm) were found in the upper part of the watershed whereas clay soils with rooting depth > 100 cm were found in the lower areas near the outlet of the catchment.

The watershed is mainly covered by agricultural land (74%) followed by forest (23%), pasture (2%) and villages. The major crops of the agricultural lands include sorghum, teff, faba bean, lentil, wheat, chick pea, linseed, fenugreek, and barley. Teff and sorghum are the main staple crops whereas chick pea is grown in the lower regions and cannot be grown as a crop in the higher altitude.

Figure 1. Overview of the project area in the northwest Amhara region, Ethiopia.

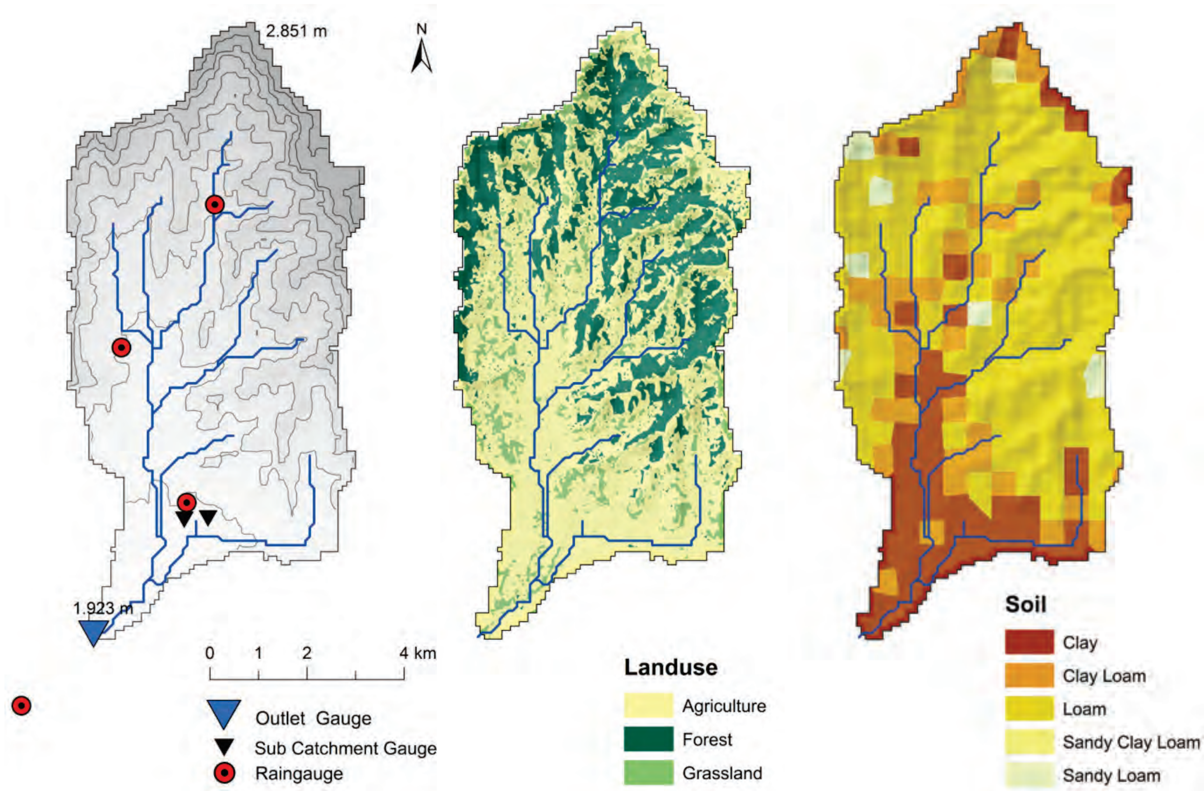
SWAT model

SWAT 2009 (Neitsch et al., 2009) and ArcGIS 9.3 was used to simulate hydrologic and sediment transport processes in daily time step resolution. Surface runoff was calculated by SCS CN method to user-friendly assess land management, soil, climate and vegetation effects (Hjemfeldt, 1991; Arnold and Allen, 1998; Baker and Miller, 2013) on runoff. Soil conservation measures were considered by modification of the cover and management factor (CUSLE) and the support practice factor (PUSLE) of the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1995).

SWAT input and calibration data

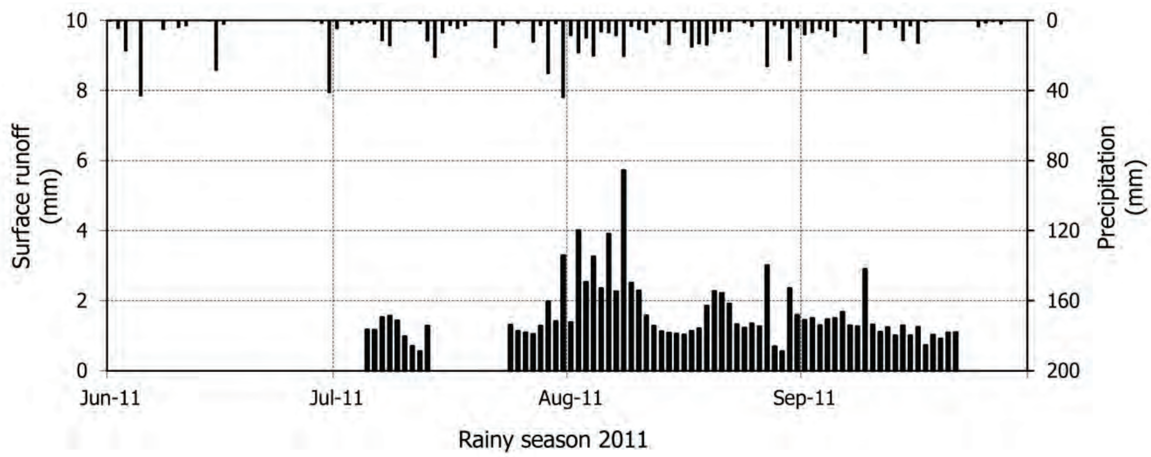
A DEM of the watershed was prepared using SRTM (Shuttle Radar Topography Mission) data with 90 m grid resolution. Land use input was prepared based on supervised SPOT satellite image classification using Erdas Imagine 9.1. A soil map was created based on 234 soil samples taken in 500 m grid across the entire watershed. Climate data was available from four different rainfall, four temperature, one solar radiation, one relative humidity, and one wind speed gauge within respectively close to the catchment. The available climate data ranges from 1997 to 2011.

Figure 2. SWAT input data: left figure shows elevation data and the locations of the gauging stations, the central figure shows land use data and the right figure shows the soil map.



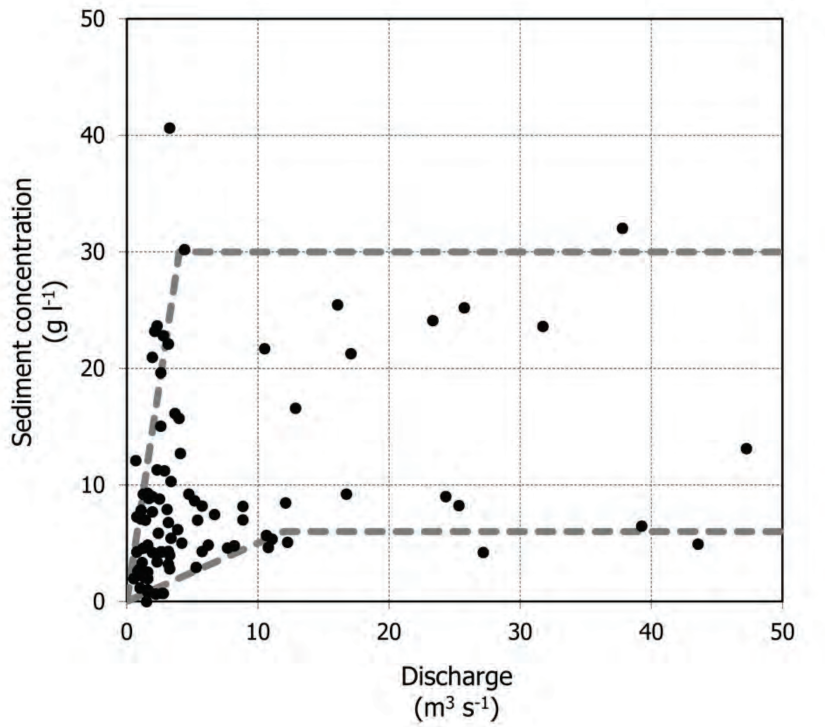
In the catchment a dense gully network cuts through the upland which strongly affects the drainage and translation processes of runoff and therefore proper delineation of the watershed is crucial. In this study, the drainage density of a representative sub-catchment was analyzed by hand-held GPS survey which indicated the average drainage area between 2 and 10 ha.
The model was calibrated based on daily runoff data at the outlet gauging station of the watershed, from 4th of July, 2011 to the 12th of July, 2011 and from 23rd of July, 2011 to 20th September, 2011. The fixed outlet cross section is equipped by a continuously logging water level sensor to calculate discharge by a rating curve established based on water level and manual flow velocity measurements using a 1D flow velocity device. Continuous discharge data was transferred into daily runoff for daily time step SWAT calibration.

Figure 3. Hydrograph at the main outlet and precipitation data from the nearest rain gauge (Outlet).



Sediment concentration was manually sampled at three stages of various flood events. As selectively sampled sediment data may not be suitable for daily based model calibration, sediment data was used to establish a relation between runoff and sediment concentration (Figure 4). Based on the manual sampling upper and lower boundaries of potential sediment concentration for certain discharge was defined.

Figure 4. Scatter plot of discharge and sediment concentration of the manual bottle sampling at the main outlet. Dashed lines indicate the lower and upper defined limit of the expected relation between discharge and sediment concentration.



Calibration and sensitivity analyses

For model calibration most affective parameters on runoff were selected based on a sensitivity analyses. Therefore auto-calibration and sensitivity-analysis of SWAT was used alternatingly to iteratively locate the controlling parameters on simulated runoff. For the sensitivity analysis each of the chosen parameter was varied in 5% steps between -20% and +20% of the expected value. After ranking the ten most sensitive parameters a manual calibration was performed and soil conservation treatments such as stone bunds and small water retention ponds were implemented in the model.

To simulate soil conservation effects of the stone bunds the curve number (CN) and practice factor (P) of HRU`s located in the central part of the watershed were manually adjusted. In this study, CN of stone bund treated HRU`s was reduced by three units, also reported by Lanckriet et al. (2012) for a watershed study in the northwestern Amhara region. For the adjustment of the P-factor different recommendations exist in the literature - for example Nyssen et al. (2007) estimated a P-factor of 0.32 for stone bund practices in a North-Ethiopian catchment and Hessel and Tenge (2008) used a P-factor of 0.50 for a watershed in Kenya. In the Gumara-Maksegnit watershed an erosion plot monitoring was carried out to evaluate on-site conditions of the stone bund measures. The monitoring indicated highly variable soil loss rates on treated and untreated field plots as soil loss was heavily affected by spatially variable stone and crop cover. Entirely, the erosion plot monitoring suggested a minor soil conservation effect of the stone bunds compared to studies of Nyssen et al. (2007) and Hessel and Tenge (2008) and consequently we decided to set the P-factor for stone bund treated fields to 0.85. Additionally, five retention ponds of 125 m³ volume were integrated in the SWAT model, even though the effect on surface runoff might be negligible for watershed level output.

Figure 5. Stone bund treated fields (left image) and the small channel above the stone bund (right image).

Nash-Sutcliffe coefficient (NSE; Nash and Sutcliffe, 1970) was used to evaluate the model performance. The Nash-Sutcliffe coefficient (NSE) is calculated by following equation:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_o - Q_s)^2}{\sum_{i=1}^{n}(Q_o - Q_{O,mean})^2} \qquad (1)$$

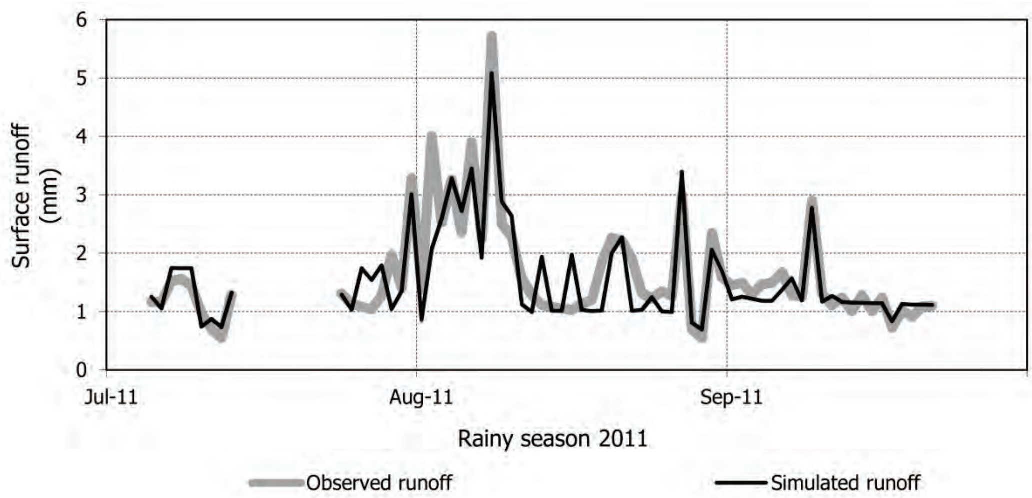
where Q_O is the observed discharge, Q_S is the simulated discharge and $Q_{O,mean}$ is the mean observed discharge.

Results

The sensitivity analysis indicated curve number (CN) as most descriptive parameter concerning runoff, followed by the base flow parameters APLHA_BF and GW_DELAY. Figure 6 illustrates observed and simulated runoff data of the calibrated model on a daily basis for the rainy season 2011. It can be seen that the peak flows are properly described and also the lower flows during short dry periods fit well to the outlet-hydrograph. The well described peak flows (Figure 6) indicate that the SCS CN procedure can be properly used for the translation of the rainwater in this watershed. Low flows are controlled by base- and interflow processes and hence APLHA_BF and GW_DELAY were most effective parameters. The calibrated model predicts ca. 2 to 5 mm mean daily runoff (ca. 0.05 to 0.10 m³ s^{-1} mean daily discharge) at the end of the dry spell (from February to April) which confirms to our field prospection. The calculated NSE (Equation 1) of observed and simulated runoff is 0.777, which indicates a “very good” model performance according to the ratings of Saleh et al. (2000) for daily runoff data using SWAT.

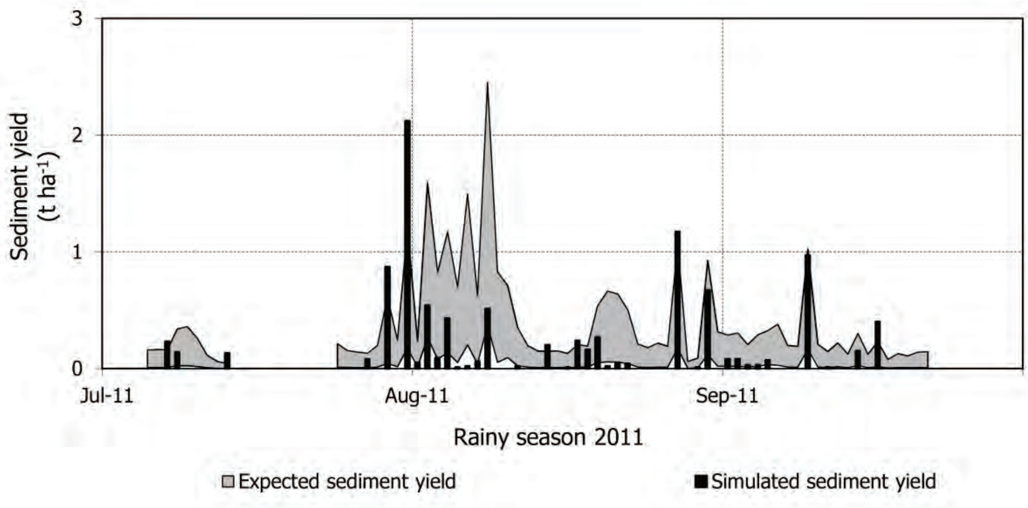
However, it should be noted that the model is not yet validated and the processing of recorded data of the rainy season 2012 is still in progress.

Figure 6. Comparison of observed and simulated runoff data at the main outlet.



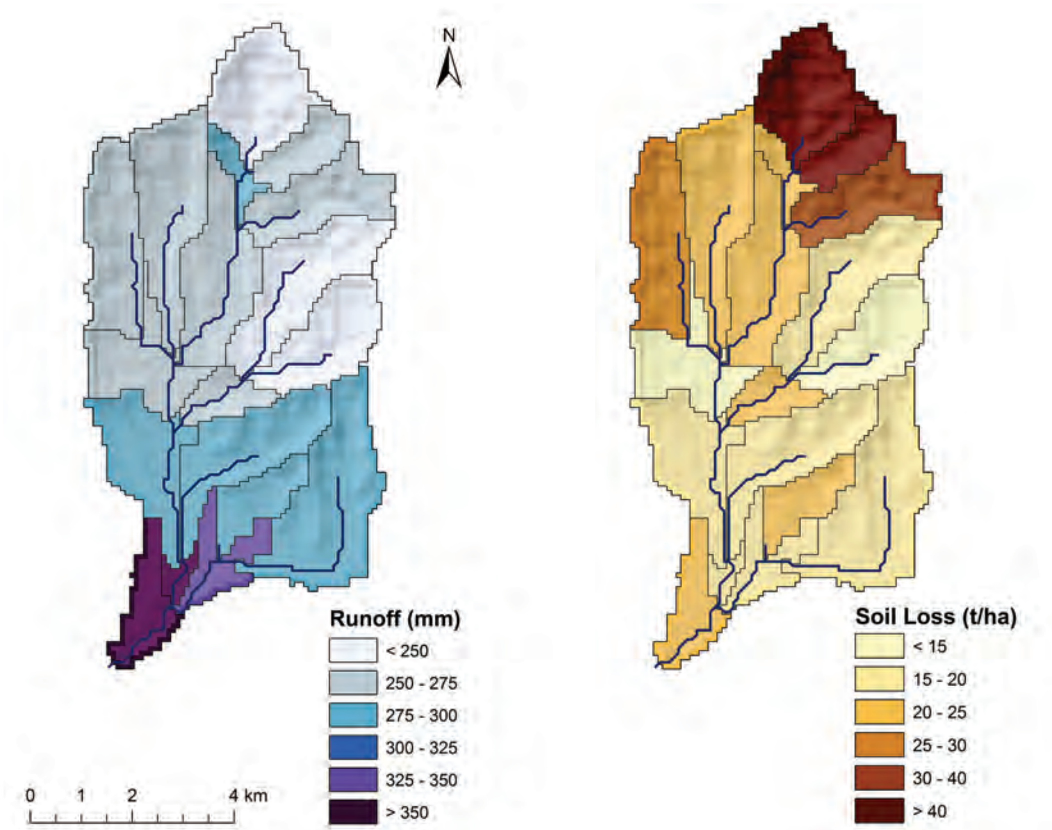
Simulated sediment yield was compared to the expected sediment yield based on manual bottle sampling (Figure 7), three times a runoff event at the outlet gauging station of the watershed. The expected sediment yield ranges between 2.9 and 27.6 t ha^{-1} whereas the model predicts 10.0 t ha^{-1} sediment yield for the observed period in 2011.

Figure 7. Comparison of the expected range of sediment yield (manual bottle sampling) and the simulated sediment yield (SWAT) at the main outlet.



To localize the hot-spot areas of surface runoff and soil loss mean annual values were calculated using climate data from 1997 to 2011. Simulated mean annual surface runoff ranges from < 250 mm in the northern watershed to > 350 mm in the southern part of the watershed (Figure 8). This might refer to the higher forest-cover in the northern areas but also to the applied stone bunds in the central part and the heavy clay soils in the southern part of the watershed. Hence, the runoff map in Figure 8 indicates a high potential for water harvesting strategies in the near outlet regions. Contrarily the soil loss map indicates highly endangered regions in the northern parts of the watershed which might refer to the remarkable steepness of the relative sub basins. Comparatively low mean annual soil loss (< 20 t ha^{-1}) occurs in the central sub basins which indicates the positive effect of local soil conservation measures already applied.

Figure 8. Mean annual runoff and soil loss predicted by SWAT.



Discussion

The hydrograph at the outlet of the watershed is dominated by the short-period peak flows, occurring several times weekly, which interrupt mean base flow of ca. 1 $m^3\ s^{-1}$ during the rainy season. Intense rainfall events correspond to peak flows in daily temporal scale (Figure 3) which states that rainwater is routed through the watershed in sub-daily time intervals. This refers to the steep sloped and small sized catchment (54 km^2) and the convective rainfall characteristics in the Ethiopian highlands. At the outlet, peak discharges of about 30 $m^3\ s^{-1}$ have been observed during field works in 2012 whereas extreme floods are expected to exceed this amount several times. Controversially, the SWAT model derives maximum mean daily discharges of less than 10 $m^3\ s^{-1}$ for whole calibration period 2011 which is a consequence of the daily based runoff computation. Thus, the erosional force of the flowing water in the channel is accordingly underestimated. Based on the fact that bottle samples at the watershed outlet provide lumped information of upland and channel sediment sources, the unclear sediment contribution of the gullies negatively affects the evaluation of upland erosion as well. In the watershed various field studies are still in progress to evaluate the seasonal gully growth and ongoing monitoring of upland erosion on a plot level is planned. However, up to now reliable determination of the proportion of upland and

channel erosion is not yet available and therefore the expectations concerning soil loss have to be considered cautiously.
Spatially variable rainfalls can harm the entire watershed model as local rainfall data recorded by any rain gauge is transferred to the nearest neighboring sub basins by the model. From our observations, on the 29th of June 2011, 90 mm of rainfall was recorded in a time period less than two hours and 124 mm of rainfall was recorded in less than five hours at the northern rain gauge in the watershed, whereas the central rain gauge recorded < 5 mm precipitation on similar day. The negative effect of up-scaling of local rainfall data is shown by some peaks in the simulated runoff in the hydrograph at which the observed runoff stagnates (and vice versa). However, based on the overall “very good” model performance according to the ratings of Saleh et al. (2000) we assume that the model assigns the sources of upland runoff - and accordingly upland soil erosion - in proper spatial distribution within the 18 sub basins, even though the magnitudes of the declared runoff and erosion rates are uncertain.

Conclusions

This study showed that SWAT can be used to simulate hydrology and sediment transport characteristics of a small and steep sloped watershed in the Ethiopian highlands on a daily basis. Moreover it was shown that SWAT allows reliable consideration of local soil conservation effects of stone bunds and small scale retention ponds.
Referring to the daily time step resolution, sub-daily watershed processes like flash floods and consequential peaks in discharge and gully erosion might be systematically underestimated by our model. This negatively affects the assignment of sediment sources (upland and channel) as the modeled sediment yield is verified by lumped sediment data monitored at the outlet of the watershed. However, predicted sediment yield fits to the expectations based on manual bottle sampling. Thus, we conclude that the calibrated model can be used to locate potential hot-spot areas concerning surface runoff and soil erosion in the uplands.
Based on the calibrated SWAT model, advanced soil conservation scenarios can be simulated to spatially optimize soil conservation and hence to support sustainable land management in the future.

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