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An efficient semi-distributed hillslope sediment model: the Anjeni in the sub humid Ethiopian Highlands

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Abstract

Prediction of sediment loss in Africa is not well developed. In most case models developed in western countries with a temperate climate do not perform well in the monsoon climate prevailing in Africa. In this paper we base our sediment prediction on a simple distributed saturated excess hydrology model that predicts surface runoff from bottom lands that become saturated during the rainy season and from severely degrade lands and interflow and base flow from the remaining portions of the landscape. By developing an equation that relate surface runoff and sediment concentration from runoff source areas assuming that base flow and interflow are sediment free, we were able to predict the daily sediment concentrations in a 113 ha Anjeni watershed in the Ethiopian Highlands with a Nash Sutcliffe efficiency ranging from 0.64–0.77 using only two calibrated sediment parameters. The daily flows were predicted with a Nash Sutcliffe efficiency values ranging from 0.80 to 0.84 based on 14% of the watershed consisted of degraded area as the only surface runoff source. The analysis seems to suggest that identifying the runoff source areas and predicting the surface runoff correctly is an important step in predicting the sediment concentration at least for the Anjeni watershed.

1 Introduction

Soil erosion has been common for an extended period of time in the Blue Nile basin in the Ethiopian highlands (Nyssen et al., 2004). Recently, due to greater population pressure and consequently more intensive cultivation, erosion losses have been increasing to an annual areal average of 7 t ha^{-1} equivalent to a depth 0.5 mm (Garzanti et al, 2006). Local erosion rates have high spatial variability ranging from less than 1 to over 400 t ha^{-1} year^{-1} (Hurni, 1988; Mitiku et al., 2006; Tebebu et al., 2010).

Future development of water resources in Ethiopia and Sudan should include reduction of soil losses. Several large dams are planned for the Blue Nile Basin and erosion will reduce reservoir capacity as currently experienced at Roseries and Aswan High Dams. In the watershed, erosion from newly developed lands represents a fertility loss. Finally soils that too become too shallow due to erosion increase surface runoff and reduce interflow (Tesemma et al., 2010).

Erosion models are an important tool in reducing soil loss in the future by predicting the location of vulnerable areas that need to be managed for reducing soils loss. Erosion models applied in the Ethiopian Highlands range from the empirical relationships (Universal Soil Loss Equation – USLE), to physical based models. Hurni (1985) adapted the empirical USLE for Ethiopian conditions. Eweg et al. (1998) and Zegeye et al. (2011) showed that the modified USLE can be used to estimate average annual soil losses but question the reliability of predicting the spatial distribution of erosion and temporal distribution shorter than a year.

From the physical models available that predict sediment load, only the Agricultural Non-Point Source Pollution (AGNPS) model (Haregeweyn and Yohannes, 2003; Mohammed et al., 2004), the Soil and Water Assessment Tool (SWAT) (Setegn et al., 2008), the modified SWAT-WB Water Balance model (Easton et al., 2010) and Water Erosion Prediction Project (WEPP) (Zeleke, 2000) are tested for the Ethiopian Highlands. Except for SWAT-WB, these models are applied with the assumption that infiltration excess runoff mechanism governs the runoff process in all areas. The application of AGNPS in Kori watershed (Haregeweyn and Yohannes, 2003) was for limited storm events and predicted the runoff and sediment with some success even though peak runoffs were not predicted well. The application of the AGNPS model in Awgucho catchment (Mohammed et al., 2004) was relatively poor for runoff production and application of WEPP in Anjeni slightly over predicts the soil plot loss for storms with low intensities, but overall Nash Sutciffe were satisfactory (Zeleke, 2000).

Other sediment models that have not been applied in the Ethiopian Highlands are Areal Nonpoint Source watershed Response Simulation (ANSWERS) (Beasley et al., 1980), European Soil Erosion Model (EUROSEM) (Morgen et al., 1998), Physical Water Erosion Model (Hairsine and Rose, 1992a,b) and GUEST (Yu et al., 1997). Besides

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shear stress (Yalin, 1963), these models use a stream power function for predicting sediment carrying capacity (Rose, 2001) where the sediment concentration at the transport limit is related to runoff depth as a power function (Ciesiolka et al., 1995; Yu et al., 1997). Limited testing of these models has been done for monsoonal climates. The Hairsine and Rose model (1992a,b) that resulted in linear relationship between sediment concentration and velocity of runoff predicted sediment concentrations successfully in the monsoon climate of the Philippines, Thailand and Malaysia using observed stream flows (Rose, 2001). In the foot hills of Nepal WEPP predicted soil erosion from USLE type plots the best followed by the GUEST Technology and EUSROSIM (Kandel et al., 2001).

The two models applied in Ethiopia using the SCS curve number approach to predict surface runoff (AGNPS, non modified SWAT) simulated daily stream discharge less than satisfactory. Implicitly, the SCS curve number assumes that plant and soil related factors determine amount of runoff while hydrology is topographically driven in the Ethiopian Highlands (Lui et al., 2008; Bayabil et al., 2010; Engda, 2011). Therefore, to improve the erosion predictions requires a runoff model that includes the proper hydrology.

Recently Steenhuis et al. (2009), White et al. (2009) and Easton et al. (2010) have developed distributed models that take the terrain topographic features into account that are suitable for monsoonal climates and can predict the runoff in the watershed based on a daily basis. The model of Steenhuis et al. (2009) is relatively simple and divides the watershed up into three distinct areas consisting of the periodically saturated bottom lands, severely degraded areas with very shallow soils over an impermeable layer and hillsides. The saturated areas and the degraded areas produce surface runoff and sediment and the hillside sediment free interflow and base flow to the river. Ten-day averaged discharge and sediment concentrations were well predicted for the Blue Nile at the border with Sudan. White et al. (2009) modified the SWAT model (SWAT-WB) by redefining the HRU's based on topography and soil depth and surface runoff was predicted as any excess rain after the soil became saturated. SWAT-WB simulated available daily sediment yield data in the Blue Nile Basin at several scales well (Easton et al., 2010). Input data requirements, however, for SWAT and SWAT-WB is cumbersome especially in areas with limited data sources such as in Ethiopia.

The objective of this study is therefore to use a reasonably accurate hydrology model validated for a monsoon climate to improve sediment concentration predictions in the Ethiopian Highlands. Since the data availability under Ethiopia conditions are extremely limited, we will use the simple semi-distributed water balance model developed by Steenhuis et al. (2009) coupled with components of a simple sediment model. The sediment model closely follows the work of the Hairsine and Rose model (1992a,b) as developed by Rose (1993) and that of Ciesiolka et al. (1995) and Yu et al. (1997) assuming that a linear relationship between sediment concentration and velocity from runoff producing areas.

Sediment concentration data are available for a few watersheds in Ethiopia. These watersheds were established by Soil Conservation Research Program (SCRP) initiated in 1981 in order to support and monitor SWC efforts in the highlands of Ethiopia by the Governments of Ethiopia and Switzerland. In this paper, we used the data of one of these experimental watershed located in the Ethiopian Highlands, Anjeni.

2 Material and methods

2.1 Description of Anjeni watershed

Anjeni is one of the seven experimental watersheds that were in operation in June 1984 as part of the Soil Conservation Research Program (SCRP), a collaborative project of the University of Berne, Switzerland, and the Ministry of Agriculture, Ethiopia. This watershed is in the Ethiopian Highland and draining into the Nile watershed.

The Anjeni watershed (Fig. 1) covers an area of 113.4 ha with elevations ranging between 2405 and 2507 m. It is located in the sub-humid northwestern part of Ethiopia near Debre Markos at 37°31′ E and 10°40′ N and lies 370 km NW of Addis Ababa to the south of the Choke Mountains. The mean annual rainfall is 1690 mm with unimodal rainy season which lasts from the middle of May to the middle of October. Mean daily temperature ranges from 9 °C to 23 °C. The watershed is oriented north-south and flanked on three sides by plateau ridges. The geological formation of the catchment area belongs to the basaltic Trap series of the Tertiary volcanic eruptions and the topography of the area is typical of Tertiary volcanic landscapes deeply incised by streams (Zeleke, 2000). There is high gully formation at the upper part of the watershed where a perennial spring is located at the head of the gully and become a source for a river called Minchet.

The soils of Anjeni have developed on the basalt and volcanic ash of the plateau. The valley floors and the depressions of the foothill land consists of deep well weathered humic Alisols while moderately deep Cambisols cover the middle area and the very shallow Regosols and Leptosols cover the hillsides indicating land degradation processes (Zeleke, 2000).

Before 1986 no management activities existed in the Anjeni watershed and was monitored without any SWC (SCRP, 2000). Fanya juus (SWC structure comprised of a bund above and a drainage ditch below the bund) were then constructed in early 1986 throughout the watershed and had generally developed into terraces by 1992 (Hanggi, 1997).

2.2 Data

Since the establishment of the micro-watershed by the Soil Conservation Research Project (SCRP) in 1984, fine resolution data on climate, hydrology, and suspended sediment, from both river and test plots, have been collected and an expansive database was established that serves as a data source to carry out hydrological, soil erosion, and conservation research activities at regional, national, and international levels. This watershed provided the most comprehensive data of daily rainfall, stream flow, and sediment concentrations (Hailu et al., 2006).

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Stream flow and sediment concentration were measured at a station located at the outlet of each watershed. The depth of water was taken with float-actuated recorders. The water level in the stream was measured daily at 08:00 a.m. In case of peak stream flow events, water level measurements and sediment samples were usually taken every 10 min interval during the event and every 30 min when water level decreased. Discharge was evaluated using the relation between the water level, and stream discharge (Bossahart, 1997). The river stage-discharge relationship was determined using salt-dilution and current-meter methods.

One liter samples were taken during the storm from the river at the gauging station to determine the sediment concentration. Sampling started once the water in the gauging station looked brown and, the sampling continued at ten minute interval. When the runoff became clearer, the sampling interval was extended to thirty minutes and sampling continued until the runoff was sediment free. The collected water samples were filtered using filter paper, sundried, and finally oven dried and weighed and net dry soil loss was calculated. For modeling purpose, event based sediment yields were summed over a daily period to determine daily sediment load. Sediment concentration was determined by dividing the daily sediment load by the total discharge during that day.

In Anjeni, the period from 1988 to 1997 was used as data source for rainfall, potential evaporation and stream flow. Periods in which there is incomplete data (for example, 1995 and 1996) were excluded from model development processes. Similar to the climate and stream flow data, sediment data are obtained for the same period except 1988, 1994 and 1997.

2.3 Methodology

Model development: conceptual model

The model is based on the concept that erosion is produced in areas with surface runoff. Thus, in our hydrology model that simulates surface runoff from saturated areas

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and degraded hillside areas, erosion is only simulated from these runoff producing source areas. Erosion is negligible from the non degraded hillsides because almost all water infiltrates. Erosion rates are greater in the more heavily degraded areas without plant cover than in the saturated source areas with natural vegetation. The only exception could be in the beginning of the rainy season in cases where these soils were used for growing a crop during the dry season. The latter is not simulated since we do not have this information available.

Event based sediment loads are converted to daily concentrations. We will show below that this directly affect how the concentrations are simulated. Two storms are depicted one in the beginning of the short rainy season (24 April 1992, Fig. 3a) and one later in the rainy season (19 July 1992, Fig. 3b) and after more than 500 mm of cumulative effective rainfall since the beginning of the rainy season and the watershed has wetted up and interflow occurs (Liu et al., 2008). The surface runoff for both events is similar with peak runoff 400–500 $L\,s^{-1}$ above the flow in the channel before the surface runoff occurred. The duration of the runoff event was approximately 2 h. The peak sediment concentrations were nearly the same around 30–35 $g\,L^{-1}$. Base flow discharge is low during the beginning of the rainy season (around 10 $L\,s^{-1}$ for April or equivalent to 0.8 $mm\,day^{-1}$ over the whole watershed). Base flow increases during the rainy season it is approximately 50 $L\,s^{-1}$ (equivalent to 4 $mm\,day^{-1}$) in July. Despite the similar surface runoff characteristics the total flow for April was $2.4 \times 10^3\,m^3\,day^{-1}$ and for July was $6.5 \times 10^3\,m^3\,day^{-1}$ The averages daily sediment concentration can be obtained by dividing the load by the total flow resulting in concentration of 11.3 $g\,L^{-1}$ for the April storm and 4.4 $g\,L^{-1}$ for the July storm. What is important to note is that in calculating the average daily stream flow data, the peak flows occur less than 10% of the time, and thus the base flow contributions when averaged over a day is a significant portion of the daily flow for the July storm when the watershed is in equilibrium. Thus in essence the base flow dilutes the peak storm concentration when simulated on a daily basis later in the rainy season. It is therefore important to incorporate the contribution of base flow in the prediction of sediment concentration.

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2.4 Model descriptions

2.4.1 Hydrology model

The watershed is divided into three regions: two surface runoff source areas consisting of areas near the river that become saturated during the wet monsoon period and the degraded hillsides with little or no soil cover. The remaining hillside areas have infiltration rates in excess of the rain fall intensity (Bayabil et al., 2010; Engda et al., 2011). Consequently the rainwater infiltrates and becomes either interflow or baseflow depending on its path to the stream. A water balance is kept for each of the regions using the Thornthwaite Mather procedure (Thornthwaite and Mather, 1955; Steenhuis and van der Molen, 1986) for calculating the actual evaporation. Overland flow is simulated when the soil is at saturation for the potentially saturated areas and the degraded hillsides. Since the soil in the degraded areas is shallow, only minor amounts of rainfall are required before the soil saturates and runoff is produced. When the soil in the hillsides reaches field capacity, additional rainfall is released to the first order baseflow reservoir and a linear interflow reservoir. More detail on the water balance and subsurface flow equations are given in Steenhuis et al. (2009) where the model was applied to the whole Blue Nile Basin using Microsoft Excel spreadsheet.

Inputs to the model are rainfall and potential evaporation and parameter to the model are the magnitude of the relative areas and the amount of storage in the soil between witling point and saturation for the runoff producing areas and wilting point and field capacity for the hillside. In addition there are three more subsurface parameters, a maximum storage and half-life for the first order ground water reservoir, the time it takes for a hillslopes to drain after a rainstorm for the linear interflow reservoir.

2.4.2 Sediment model

For these two source areas, the mean suspended sediment concentration C ($\mathrm{g\,L^{-1}}$) is a function of flow rate and a coefficient dependent on landscape and sediment

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characteristics (Hairshine and Rose, 1992a,b; Rose et al., 1993; Siepel et al., 2002; Ciesiolka et al., 1995; Yu et al., 1997),

$$C = aQ^n. \tag{1}$$

Where Q is the runoff rate per unit area from each source areas (mm), a is a constant which is a function of the slope, Manning's roughness coefficient, slope length, and the effective depositability (Yu et al., 1997) and n is the exponential that takes a value of 0.4 assuming a linear relationship between sediment concentration and velocity and wide channel on the runoff producing areas (Ciesiolka et al., 1995; Yu et al., 1997). Sediment yield (t day^{-1}), Y_i, for each of the two runoff source areas, i, becomes then

$$Y_i = Q_i \times Q_i^{0.4} \times a. \tag{2}$$

To calculate the suspended sediment concentration at the watershed outlet, we note that the discharge Q_T can be written in terms of the contributions of the three areas delineated in the watershed.

$$Q_{T_t} = A_1 Q_{1_t} + A_2 Q_{2_t} + A_3(Q_{\mathrm{BF}_t} + Q_{\mathrm{IF}_t}), \tag{3}$$

where Q_{1_t} and Q_{2_t} are the runoff rates expressed in depths units for contributing area A_1 (fractional saturated area) and A_2 (fractional degraded area in %), respectively. A_3 is the fractional contributing area for baseflow , Q_{BF_t} and interflow Q_{IF_t}.

Sediment yield in the stream depends on the amount of suspended sediment delivered by each component of the stream flow. The daily sediment yield equation is in its most general form is:

$$Y_t = A_1 Q_{1_t} C_{1_t} + A_2 Q_{2_t} C_{2_t} + A_3(Q_{\mathrm{BF}_t} C_{\mathrm{BF}_t} + Q_{\mathrm{IF}_t} C_{\mathrm{IF}_t}). \tag{4}$$

Where $C_{1,2,\mathrm{BF},\mathrm{IF}}$ are the sediment concentration of the attributed component. Recalling that sediments concentration, C, is related to the discharge as shown in Eq. (1), Eq. (4) can be rewritten as:

$$Y_t = a_1 A_1 Q_{1_t}^{n+1} + a_2 A_2 Q_{2_t}^{n+1} + A_3(a_{\mathrm{BF}} Q_{\mathrm{BF}_t}^{n+1} + a_{\mathrm{IF}} Q_{\mathrm{IF}_t}^{n+1}). \tag{5}$$

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Which simplifies to a relationship between sediment yield and discharge for $n = 0.4$

$$Y_t = a_1 A_1 Q_{1_t}^{1.4} + a_2 A_2 Q_{2_t}^{1.4} + A_3 (a_{BF} Q_{BF_t}^{1.4} + a_{IF} Q_{IF_t}^{1.4}). \quad (6)$$

The superscript of Q in Eq. (6) is within the range from 0.5 to 2 in the most common sediment transport capacity models (Prosser and Rustomji, 2000). In the Anjeni watershed, we taken the sediment concentration from the base and interflow is taken as zero (i.e., $a_{BF} = 0$ and $a_{IF} = 0$) and the concentration can be obtained dividing Eq. (6) by the total discharge (Eq. 4).

$$C_t = \frac{a_1 A_1 Q_{1_t}^{1.4} + a_2 A_2 Q_{2_t}^{1.4}}{A_1 Q_{1_t} + A_2 Q_{2_t} + A_3 (Q_{BF_t} + Q_{IF_t})} \quad (7)$$

Where all parameters can be obtained from the hydrologic simulation with the exception of a_1 and a_2 that need to be calibrated with existing field data.

3 Model calibration and validation

The next step is to calibrate first daily values of the discharge with the water balance and then subsequently the sediments concentrations with the sediment model. For calibration of the water balance model, the daily rainfall, potential evaporation, stream flow data of year 1988 and 1990 were used and 1989, 1991–1994 and 1997 were used for validation. Sediment concentrations data for the same years except 1988 were also available. However, the sediment data for 1995 and 1996 were not used here because of incomplete data for the climate. The year 1989 was excluded because of very low sediment concentration measured. The low concentration might have been caused by bunds installed (Fanny juu) in the watershed in 1986 that captured effectively all sediment. Equilibrium was likely established in 1990, when the terraces were formed behind the bunds in the runoff source area. In the non source area terrace were established in 1992 (Hanggi, 1997). Consequently, the year 1990 was used for calibration and the period 1991–1993 was used for validation in the sediment modeling.

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For the hydrology model all nine input parameters were calibrated. For partitioning the rainfall in to surface runoff and recharge for sub-surface reservoirs, they consisted of the size (A) and the maximum storage capacity (S_{max}) for the three areas, and for the subsurface they involved the half life ($t_{1/2}$) and maximum storage capacity (BS_{max}), of linear aquifer and the drainage time of the zero order reservoir (τ^*). In the sediment model, there are two calibration parameters consisting of the constants for each two runoff source areas a_1 and a_2 from Eq. (7).

During model calibration and validation period, the Nash-Sutcliffe coefficient (NSE), coefficient of determination (R^2) and the Root Mean Squared Error (RMSE) were used to evaluate the performance.

4 Results and discussion

The calibrated input parameters are shown in Table 1 and the the goodness of fit, Nash-Sutcliffe coefficient (NSE), coefficient of determination R^2 and Root mean squared error (RMSE) for the hydrology and sediment model are presented in Table 2. A comparison of predicted and observed stream flow and then sediment concentration for the watershed are shown in Figs. 4 and 5, respectively.

4.1 Hydrology model

The model calibration suggests (Table 1) that 14% of the Anjeni watershed area consists of degraded area with shallow soil or exposed hardpan, which requires only a little rain to generate direct runoff (i.e., $S_{max} = 10$ mm) and approximately 2% of the saturated bottom lands in the watershed needed 70 mm of effective precipitation to generate runoff (i.e., $S_{max} = 70$ mm). The hillside or the infiltration (recharge) areas in Anjeni represent 50% of the total area and require 100 mm of effective precipitation to reach field capacity from wilting point. Flow from the remaining 34% of the watershed in Anjeni is not accounted for and leaves the watershed as deep regional flow.

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The small proportion of saturated area is consistent with the piezometer readings of Leggesse (2009) that showed a deep water table throughout the the uniformly steep watershed except in very close proximity to the stream (Fig. 2). This is unlike the Maybar (Bayabil et al., 2010) and Andit Tid (Engda et al., 2011) watersheds where large flat areas near the river usually saturate during the rainy season with annual precipitation over 1000 mm (Liu et al., 2008). In the Anjeni watershed where the soil are deep at the middle and lower part and there are no flat areas all the water that otherwise would have saturated the soil drains directly into the stream. This coincides with Collick et al. (2009) for Anjeni watershed where the author found that 35% of the watershed required higher moisture to be hydrologically active. The maximum base flow storage (BS_{max}) was calibrated to be 100 mm and τ^* was 10 days for the watershed. The half-life for the base flow storage was set to be 70 days.

Figure 4 distinctly shows that the model simulates discharge in the watershed considerably well both during calibration and validation. The R^2, NSE and RMSE values (Table 2) were 0.88, 0.84 and 1.29 mm, respectively for calibration and 0.82, 0.80 and 1.19 mm for validation indicating that the model has reasonably captured the watershed response to rainfall. Despite the good statistics, the model over predicted low flows and under predicted flows of greater than 20 mm day^{-1} during the calibration period (Fig. 4a). During validation (Fig. 4b), there is a reasonable agreement between observed and predicted for low flows, even though there is under prediction for flows than 20 mm day^{-1}. The overestimation of low flows early in the period of 1988–1990 is likely due to the impact of the implementation of Fannu juu (SWC with bunds and drainage ditches) in 1986 in the watershed. Poor maintenance of the SWC practice after 1990 in the watershed (Bosshart, 1997) reduced infiltration capacity on the hill slope and the expansion of the gully at the upper part of the watershed (Ashagre, 2009) might have led to the higher measurement of runoff as compared to previous years.

The simple model was able to simulate the discharge pattern quite well in the watershed. The R^2 and NSE values were improved over the Collick et al. (2009) spreadsheet model and Easton (2010) SWAT-WB model. This model recognizes that the initial rains

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following the dry season first need to replace the water that has been lost due to evaporation during the dry season before the watershed discharge can begin to respond to precipitation (Liu et al., 2008). This is different than most models that are developed in temperate climate in which the SCS curve number is used for predicting runoff. In the SCS curve number, only the rainfall in five days prior to the runoff event is considered to determine the runoff amount can therefore not include the cumulative effect of the dry season.

4.2 Sediment model

From the results and assumptions of the hydrology model, there are two surface runoff source areas in the watershed. We assume that these runoff source areas are sources of sediment in our modeling. The simulation showed that the degraded/rocky runoff source area represented by a constant a_2 in Table 1 generates most of the erosion. Because of the low proportion of flat lands in the watershed, sediment transported by the runoff from saturated source areas was relatively low. The assumption that no sediment concentration is generated from interflow and base flow seems to be reasonable as the agreement between observed and predicted sediment concentration deteriorates rapidly in the trial of increasing the coefficients a_{IF} and a_{BF} from zero. The finding that a small portion of the watershed (14%) delivers sediment is also shown by the study of Easton et al. (2010) for multi-watersheds in the Blue Nile Basin.

Coefficient of determination, R^2, values of 0.8 and 0.7 were found between measured and modeled daily suspended sediment concentration during calibration and validation period, respectively (Table 2). The Nash-Sutcliffe efficiency was also relatively better by getting 0.77 for calibration and 0.64 for validation. These results are comparable with the work of Easton et al. (2010) that used the modified SWAT-WB for monsoonal climate and the work of Zeleke (2000) that used WEPP. Our model uses only two parameters, whereas SWAT and WEPP models incorporate more calibration parameters such as plant cover, slope, soil and water management or soil type. Since such factors interact to affect soil erosion at a spot, sediment data homogenization is a very challenging task.

This makes sediment modeling very difficult. Therefore, getting these much coefficient of determination and NSE for daily data using only two calibration parameters is highly valued.

Despite the good fit, the model underpredicted sediment concentrations during high measurements and overestimates during low measurements (Fig. 5a,b). This occurred during the validation period specifically in 1992 and 1993. This is likely due to, first, the error in hydrology modeling propagated easily to sediment concentration simulation. Secondly, it is reported in Bosshart (1997), that poor maintenance of SWC in the watershed during these years resulted higher sediment concentration.

The incorporation of base flow and interflow in the model helps to capture the higher sediment concentration before July and the lower sediment concentration after July. Steenhuis et al. (2009) failed to capture the drop in sediment concentration at the end of July for the whole Blue Nile Basin while this model was able to do so (Fig. 5a, b). The drop and subsequent low sediment concentration at the end of the rainy season is also reported in Tigray, the northern part of Ethiopia by Vanmaercke et al. (2010). They argued that concentrations of sediment are due to sediment depletion. Others (Descheemaeker et al., 2006; Bewket and Sterk, 2003) suggested that the lower sediment concentrations are a result of the increased plant cover. Although this effect could exist, Tebebu et al. (2010) showed for the Debre Mawi watershed that such a relationship does not exist. In the Blue Nile Basin, it seems that base flow and interflow plays an important role in diluting the sediment after July and decreasing the sediment concentration.

The low sediment concentration measurements in 1989 due to SWC were difficult to capture using the model and hence excluded from the data set. This justifies that incorporating more calibration parameters, such as SWC management for the different runoff areas might improve the sediment concentration prediction.

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5 Conclusions

A simplified spreadsheet sediment model coupled with a hydrology model was developed and used to simulate sediment concentrations and runoff in an Ethiopian highland watershed, Anjeni. Such models that require very few of calibration parameters to simulate the runoff and sediment transport are important in the data limiting environment. Using these models, it was possible to define the runoff sources areas which are also sources of sediment. The analysis showed that 14% of the watershed is runoff source areas contributing major sediment to the stream in Anjeni watershed. We also found that base flow and interflow are the driving mechanism in diluting and then reducing sediment concentration after July in the Ethiopian Highlands. Our findings suggest that only relatively small portions in the watershed contribute to sediment. Situating soil and water conservation practices in those areas might be most beneficial to reduce soil erosion per unit cost.

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Table 1. Input parameters for daily stream flow and sediment concentration modeling in the Anjeni watershed.

Watersheds	Component	Area (fraction)	S_{max} (mm)	Symbol	Constant
Anjeni	Baseflow	0.50	100	a_{BF}	0.00
	Interflow			a_{IF}	0.00
	Saturated Area	0.02	70	a_1	1.14
	Degraded Area	0.14	10	a_2	4.7
	$t_{1/2} = 70$ days	$BS_{max} = 100$ mm	$\tau^* = 10$ days		

S_{max} is maximum water storage capacity, $t_{1/2}$ is the time it takes in days to reduce the volume of the base flow reservoir by a factor of two under no recharge conditions, BS_{max} is maximum base flow storage of linear reservoir; τ^* is the duration of the period after a single rainstorm until interflow ceases, a_i is calibrated parameter in sediment concentration model for components of base flow (BF), interflow (IF), saturated area (1) and degraded area (2).

Table 2. Discharge (Q) and sediment concentration simulation efficiency as evaluated by statistical measures for daily time step in Anjeni watershed.

Modeling component	Year	Mean Daily Q (mm)		Std Deviation Q (mm)		Statistical Values		
		Observed	Modeled	Observed	Modeled	E	R^2	RMSE (mm)
Hydrology	Calibration (1988, 1990)	2.06	2.27	3.20	3.59	0.84	0.88	1.29
	Validation (1989, 1991–1997)	1.88	1.93	2.68	2.79	0.80	0.82	1.19
Sediment Concentration	Calibration (1990)	0.74	0.81	2.27	2.38	0.77	0.81	1.66
	Validation (1991–1993)	0.72	0.82	2.30	2.20	0.64	0.69	1.32

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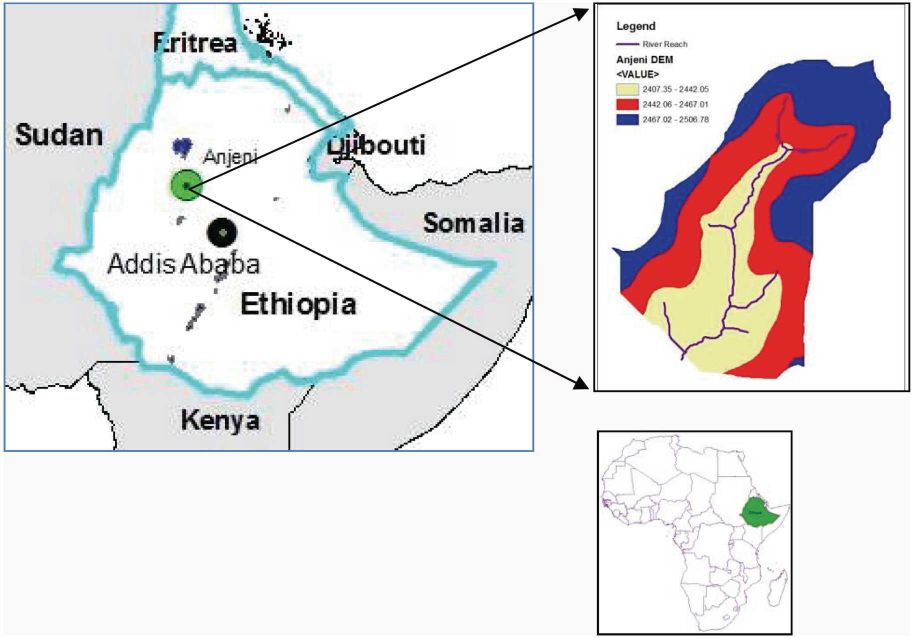

Fig. 1. Location, watershed boundary and drainage map of Anjeni watershed.

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Fig. 2. Flank portion of the watershed which was developed to full terraces from Fany Juu conservation practice in the Anjeni watershed.

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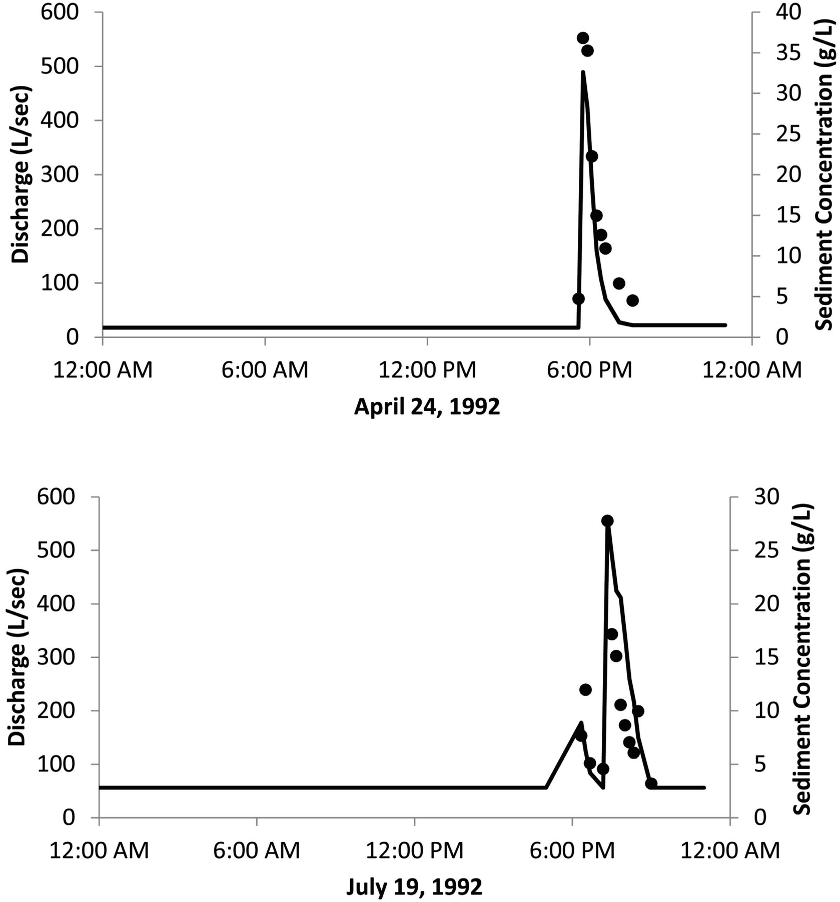

Fig. 3. Measured discharge ($L\,s^{-1}$) and sediment concentration ($g\,L^{-1}$) during **(a)** 24 April 1992 and **(b)** 19 July 1992 for Anjeni watershed.

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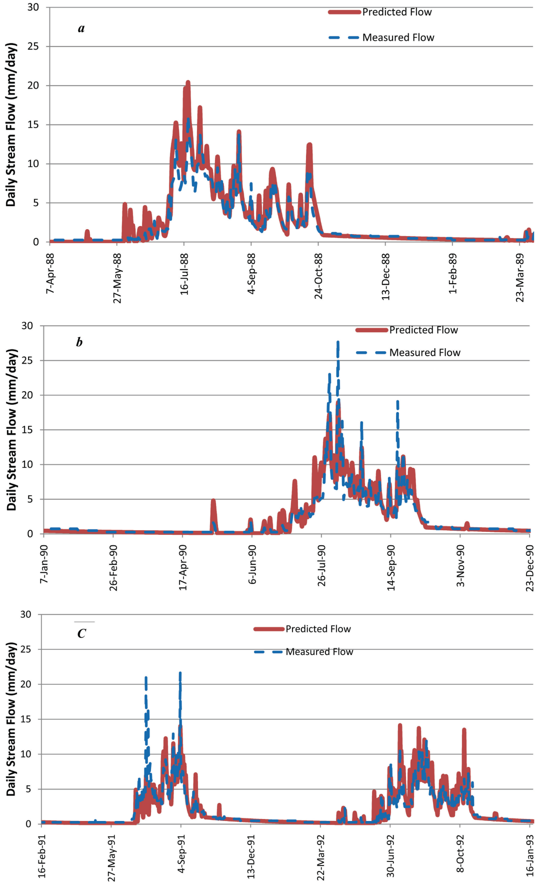

Fig. 4. Predicted and observed daily stream flow for Anjeni watershed **(a)** and **(b)** calibrated discharge using 1988 and 1990 daily data **(c)** Validated discharge (shown only 1991 and 1992).

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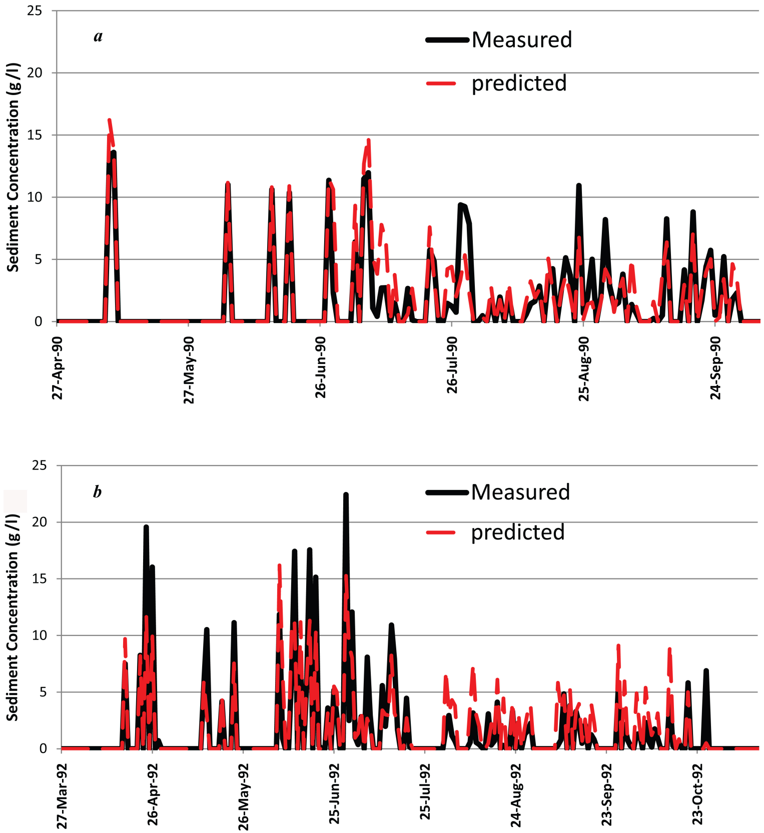

Fig. 5. Predicted and observed daily sediments concentration for the Anjeni watershed **(a)** calibrated 1990 and **(b)** validated period (shown only 1992).

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