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# Sediment management modelling in Blue Nile Basin using SWAT model

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## Abstract

Soil erosion/sedimentation is a colossal problem that has menaced water resources development in the Nile, particularly in Eastern Nile (Ethiopia, Sudan and Egypt). An insight into soil erosion/sedimentation mechanism and mitigation methods plays an indispensable role for the sustainable water resources development in the region. This paper presents a daily sediment yield simulation in the Upper Blue Nile under different Best Management Practices (BMPs) scenarios. The scenarios were baseline (existing condition), Buffer strips, stone bund (parallel terrace), and reforestation. The Soil and Water Assessment Tool (SWAT) was used to model soil erosion, identify soil erosion prone areas and assess the impact of BMPs on sediment reduction. The study found satisfactory agreement between daily observed and simulated sediment concentration with Nash-Sutcliffe efficiency (NSE)=0.88, percent bias (PBIAS)=−0.05%, and ratio of the root mean square error to the standard deviation of measured data (RSR)=0.35 for calibration and NSE=0.83, RSR=0.61 and PBIAS=−11% for validation. The sediment yield for baseline scenario was $117\times10^6\,\mathrm{t\,yr^{-1}}$. The buffer-strips, stone-bund and reforestation reduced the sediment yield at outlet of the Upper Blue Nile basin by 44%, 41% and 11%, respectively. The sediment reduction at subbasins outlets varied from 29% to 68% by buffer strip, 9% to 69% by stone-bund and 46% to 77% by reforestation. This study clearly demonstrates the efficacy of catchment management intervention (BMPs) for sustainable water resources development in the Eastern Nile basin.

## 1 Introduction

The Blue Nile River, which originates from the steep mountains of the Ethiopian Plateau, is the major source of sediment load in the Nile basin. Soil erosion upstream and the subsequent downstream sedimentation has been a colossal problem menacing the existing and future water resources development in the Nile basin. The benefits gained by construction of micro-dams in the Upper Nile, have been threatened by the rapid loss of storage volume due to excessive sedimentation (El-Swaify and Hurni, 1996; Tamene et al., 2006). Moreover, the green water storage of the Ethiopian highlands has dwindled because of top soil loss where rainfed agriculture is prevailing and induced frequent agricultural drought (Hurni, 1993; El-Swaify and Hurni, 1996). On the downstream part of the basin (e.g., in Sudan and Egypt) excessive sediment load has demanded for massive operation cost of irrigation canals desilting, and sediment dredging in front of hydropower turbines. For example, the Sinnar dam has lost 65% of its original storage after 62 yr operation (Shahin, 1993) and the other dams (e.g., Rosieres and Khashm el Girba) lost similar proportions since construction (Ahmed, 2004). Both the Nile Basin Initiative and the Ethiopian government are developing ambitious plans of water resources projects in the Upper Blue Nile basin, locally called the Abbay basin (BCEOM, 1998; World Bank, 2006). Thus, an insight into soil erosion/sedimentation mechanism and mitigation measures plays an indispensable role for the sustainable water resources development in the region.

Literature shows several catchment models that are proven to understand soil erosion/sedimentation processes and mitigation measures (Merritt et al., 2003; Borah and Bera, 2003). Nevertheless, there are a few applications of erosion modelling in the Upper Blue Nile basin. These include Zeleke (2000), Haregeweyn and Yohannes (2003), Mohamed et al. (2004), Hengsdijk et al. (2005), Steenhuis et al. (2009), and Setegn et al. (2010). Zeleke (2000) simulated soil loss using the Water Erosion Prediction Project (WEPP) model and the result slightly underestimated the observed soil loss in the Dembecha catchment (27 100 ha). Haregeweyn and Yohannes (2003) applied the Agricultural Non-Point Source (AGNPS) model and well predicted sediment yield in the Augucho catchment (224 ha). The same AGNPS model was used by Mohamed et al. (2004) to simulate sediment yield in the Kori (108 ha) catchment and the result was satisfactory. Hengsdijk et al. (2005) applied the Limburg Soil Erosion Model (LISEM) to simulate the effect of reforestation on soil erosion in the Kushet – Gobo Deguat catchment (369 ha), and the result was contentious (Nyssen et al., 2005). The SWAT model was employed for simulation of a sediment yield by Setegn et al. (2010) in the Anjeni gauged catchment (110 ha) and the obtained result was quite acceptable. Steenhuis et al. (2009) calibrated and validated a simple soil erosion model in the Abbay (Upper Blue Nile) basin and reasonable agreement was obtained between model predictions and the 10-day observed sediment concentration at El Diem located at the Ethiopia-Sudan border.

Most of the above applications are successfully attempted to estimate sediment yield at small catchment scale or evaluate soil erosion model. Yet literature shows a lack of information on mitigation measures in the upper Blue Nile basin. Therefore, the objective of this study is to model the spatially distributed soil erosion/sedimentation process over the Upper Blue Nile basin at a daily time step and assess the impact of different catchment management interventions on soil erosion and ultimately on sediment yield.

A brief description of the Upper Blue Nile Basin is given in the next section, followed by discussion of the methodology used. The third section presents the model results and discussion of different land management scenarios. Finally, the conclusion summarizes the main findings of the investigation.

## 2 Description of study area

The Upper Blue Nile River basin has a total area of 184 560 km$^2$, and is shown in Fig. 1. The Ethiopian Plateau has been deeply incised by the Blue Nile River and its tributaries, with a general slope to the northwest. The elevation ranges from 500 m at Sudan border to 4230 m at the top of highlands. The Didessa and Dabus tributaries, draining the south-western part of the basin contribute about one third of the total flow. The climate over the Blue Nile is governed by the seasonal migration of the Inter Tropical Convergence Zone ITCZ from south to north and back. The annual rainfall varies from 900 mm near the Ethiopia/Sudan boarder to 2200 mm over Didessa and Dabus. Since the rainfall is highly seasonal, the Blue Nile possesses a highly seasonal flood regime with over 80% of annual discharge (~50 billion m$^3$) occurring in the four months from July to October, while 4% of the flow occurs during the driest period from

January to April (Sutcliffe and Parks, 1999). In the basin the minimum and maximum temperatures are 11 °C and 18 °C, respectively. The dominant soil types are Alisols and Leptosols 21%, followed by Nitosoils 16%, Vertisols 15% and Cambisols 9%.

## 3 Methodology

### 3.1 SWAT model description

The Soil and Water Assessment Tool (SWAT) is a physical process based model to simulate the process at catchment scale (Arnold et al., 1998; Neitsch et al., 2005). The catchment is divided into hydrological response units (HRU) based on soil type, land use and slope classes. The hydrology computation based on daily precipitation, runoff, evapotranspiration, percolation and return flow is performed at each HRU. The SWAT model has two options for computing surface runoff: (i) the Natural Resources Conservation Service Curve Number (CN) method (USDA-SCS, 1972) or (ii) the Green and Ampt method (Green and Ampt, 1911). Similarly, there are two options available to compute peak runoff rate: (i) the modified rational formula (Kuichling, 1989) or (ii) the SCS TR-55 method (USDA-SCS, 1986). The flow routing in the river channels is computed using the variable storage coefficient method (Williams, 1969), or Muskingum method (Chow, 1959). SWAT includes three methods for estimating potential evapotranspiration: (i) Priestley-Taylor (Priestley and Taylor, 1972), (ii) Penman-Monteith (Monteith, 1965) and (iii) Hargreaves (Hargreaves and Riley, 1985).

SWAT employs the Modified Universal Equations (MUSLE) to compute HRUs soil erosion. It uses runoff energy to detach and transport sediment (Williams and Berndt, 1977). The sediment routing in the channel (Arnold et al., 1995) consists of channel degradation using stream power (Williams, 1980) and deposition in channel using fall velocity. Channel degradation adjusted using USLE soil erodibility and channel cover factors.

### 3.2 SWAT model setup

The SWAT model inputs are Digital Elevation Model (DEM), landuse map, soil map, and weather data. The DEM was used to delineate the catchment and provide topographic parameters such as overland slope and slope length for each subbasin. The catchment area of the Upper Blue Nile was delineated and discretized into 15 subbasins using a 90 m DEM (http://srtm.csi.cgiar.org) through an ArcSWAT interface (Winchell et al., 2007).

The landuse map of the Global Land Cover Characterization (GLCC) was used to estimate vegetation and their parameters input to the model. The GLCC is part of the United States Geological Survey (USGS) database, with a spatial resolution of 1 km and 24 classes of landuse representation (http://edcsns17.cr.usgs.gov/glcc/glcc.html). The parameterization of the landuse classes (e.g. leaf area index, maximum stomatal conductance, maximum root depth, optimal and minimum temperature for plant growth) is based on the available SWAT landuse classes. Table 1 shows the land use and land cover types and their area coverage in the Upper Blue Nile. The land cover classes derived are Residential area 0.2%, Dryland Cropland 17%, Cropland 5.8%, Grassland 2.5%, Shrubland 1.1%, Savanna 68.8%, Deciduous Forest 0.02%, Evergreen Forest 1.6%, Mixed Forest 0.7%, Water Body 2.2%, and Barren 0.4%.

The soil types for the study area were extracted from the SOIL-FAO database, Food and Agriculture Organization of the United Nations (FAO, 1995). There are around 5000 soil types, at a spatial resolution of 10 km with soil properties for two layers (0–30 cm and 30–100 cm depth). The soil properties (e.g. particle-size distribution, bulk density, organic carbon content, available water capacity, and saturated hydraulic conductivity) were obtained from Batjes (2002).

The USGS landuse, the FAO soil and the slope class maps were overlaid together to derive 1747 unique HRUs. Although the SWAT model provides an option to reduce the number of HRUs in order to enhance the computation time required for the simulation, we considered all of the HRUs to evaluate the watershed management intervention impact.

The daily precipitation and maximum and minimum temperature data at 17 stations interpolated spatially over the catchments were used to run the model. Most of the stations were either established recently or had a lot of missing data. Therefore, a weather generator based on monthly statistics was used to fill in the gaps. Solar radiation and wind speed were generated by the weather generator.

Daily river flow and sediment concentration data measured at El Diem gauging station (see Fig. 1) were used for model calibration and validation. The flow observations were available throughout the year, while the sediment concentration was usually monitored during the main rainy season, June to October. The Blue Nile water is relatively sediment free during the remaining months.

The model was run daily for 14 yr; the period from 1990 to 1996 was used for calibration whereas the period from 1998 to 2003 was used for validation period. The modelling period selection considered data availability and eschewed rapid landuse/cover change that was documented as alarming until the late 1980's by Zeleke et al. (2000) and Zeleke and Hurni (2001). A daily flow and sediment discharge were used to calibrate and validate the model at El Diem gauging station, located at the Ethiopia-Sudan border. Although we know that calibrating the model at subbasins outlet would improve the spatial parameter distribution, we could not perform it due to lack of data. Sensitivity analysis was carried out to identify the most sensitive parameters for model calibration using One-factor-At-a-Time (LH-OAT), an automatic sensitivity analysis tool implemented in SWAT (van Griensven et al., 2006). Those most sensitive parameters were automatically calibrated using Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour et al., 2004, 2007).

## 3.3 Model performance evaluation

Model evaluation is an essential measure to attest the robustness of the model. In this study three model evaluation methods – (i) Nash-Sutcliffe efficiency (NSE), (ii) percent bias (PBIAS), and (iii) ratio of the root mean square error to the standard deviation of measured data (RSR) – were employed following Moriasi et al. (2007) model evaluation guidelines. The Nash-Sutcliffe efficiency (NSE) is computed as the ratio of residual variance to measured data variances (Nash and Sutcliffe, 1970), see Eq. (1).

$$\mathrm{NSE} = 1 - \left[ \frac{\sum_i^n \left( X_i^{\mathrm{obs}} - X_i^{\mathrm{sim}} \right)^2}{\sum_i^n \left( X_i^{\mathrm{obs}} - X^{\mathrm{mean}} \right)^2} \right] \tag{1}$$

Where: $X_i^{\mathrm{obs}}$=observed variable (flow in m$^3$/s or sediment concentration in mg/l), $X_i^{\mathrm{sim}}$=simulated variable (flow in m$^3$/s or sediment concentration in mg/l), $X^{\mathrm{mean}}$=mean of $n$ values, $n$=number of observations.

The NSE value ranges between $-\infty$ and 1; a value between 0 and 1 indicates acceptable model performance whereas a value less than 0 indicate poor model performance (Nash and Sutcliffe, 1970).

The Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999), see Eq. (2).

$$\mathrm{PBIAS} = \left[ \frac{\sum_i^n \left( X_i^{\mathrm{obs}} - X_i^{\mathrm{sim}} \right) \times 100}{\sum_i^n \left( X_i^{\mathrm{obs}} \right)} \right] \tag{2}$$

The optimal value of PBIAS is 0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999).

The ratio of root mean square error to the standard deviation of measured data (RSR) is calculated as the ratio of the Root Mean Square Error (RMSE) and standard deviation of the observed data (Moriasi et al., 2007), see Eq. (3):

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\mathrm{STDEV}_{\mathrm{obs}}} = \left[ \frac{\sqrt{\sum_{i}^{n} \left( X_i^{\mathrm{obs}} - X_i^{\mathrm{sim}} \right)^2}}{\sqrt{\sum_{i}^{n} \left( X_i^{\mathrm{obs}} - X^{\mathrm{mean}} \right)^2}} \right] \tag{3}$$

RSR varies from zero (optimal) to a large positive value. The lower RSR, the lower is the RMSE, and hence better the model performance (Moriasi et al., 2007).

### 3.4 Catchment management intervention scenarios

Catchment management intervention involves an introduction of best management practices (BMPs) to curb soil erosion and sediment transport. The SWAT model was applied to simulate the impact of BMPs on sediment reduction in the USA (Vache et al., 2002; Santhi et al., 2005; Bracmort et al., 2006). The BMPs were represented in the SWAT model by modifying SWAT parameters to reflect the effect the practice has on the processes simulated (Bracmort et al., 2006). However, the type of BMPs and their parameter value selection is site specific and ought to reflect the study area reality. Thus, we cautiously selected appropriate BMPs and their parameter value based on documented local research experience in the Ethiopian highlands (Hurni, 1985; Herweg and Ludi, 1999; Gebremichael et al., 2005). The three selected BMPs were (i) buffer strips, (ii) stone bund (parallel terrace locally build from stone along the contour), and (iii) reforestation. Each BMP has a different effect on flow and sediment variables, and hence represented by distinct parameter(s) in SWAT. Table 2 shows the SWAT parameters used to represent BMPs. The parameter used to simulate the effect of buffer strip is width of filter strip (FILTERW). Whereas, the effect of stone bund was simulated using Curve Number (CN2), slope length (SLSUBBSN) and USLE support practice factor (USLE_P). The reforestation effect was simulated by introducing land use change.

A total of four model scenarios were run, including base scenario, as depicted in Table 2. Scenario-0 (baseline) was implemented without BMPs to reflect the existing condition. Scenario-1 (buffer strip) was implemented on agricultural HRUs that are the combination of dryland cropland, all soil types and slope classes. The effect of the buffer strip is that it filters the runoff and traps the sediment in a given plot (Bracmort et al., 2006). We simulated the impact of buffer strip on sediment trapping by assigning FILTERW value of 1 m. This filter width value was assigned based on local research experience in the Ethiopian highlands (Hurni, 1985; Herweg and Ludi, 1999).

Scenario-2 (stone-bund) was applied on agricultural HRUs that are a combination of dryland cropland, all soil types and slope classes 0–10% and 10–20%. This practice has a function to reduce overland flow, sheet erosion and reduce slope length (Bracmort et al., 2006). SWAT assigns the SLSUBBSN parameter value based on the slope classes. In this application the assigned values by the SWAT were 61 m, 24 m and 9.1 m for slope class 0–10%, 10–20% and greater than 20%, respectively. The modified parameters values were SLSUBBSN is equal to 10 m for slope class 0–10% and 10–20% classes, USLE_P is equal to 0.32, and CN2 is equal to 59 as is depicted in Table 2. The SLSUBBSN represents the spacing between successive stone bunds at field condition and the modified value was used as reported by Hurni (1985) and Herweg and Ludi (1999). Similarly, USLE_P value was obtained from documented field experience by Gebremichael et al. (2005). Whereas, the CN2 value was obtained from the SWAT user's manual version 2005 for contoured and terraced condition (Neitsch et al., 2005).

In Scenario-3 (reforestation), we simulated the impact of reforestation on sheet erosion. The reforestation has a function to reduce rainfall erosivity since it provides good cover and hamper overland flow. It was deemed impractical to change agricultural land into forest completely. Thus we supplanted 8% of the area occupied by cropland, shrubland, barren, mixed forest, and deciduous forest into evergreen forest. The evergreen forest was selected because it provides adequate cover against rainfall through out the year. In addition, the evergreen forest could be easily adapted since it has larger area coverage as compared to other forest type, see Table 1. The parameters used to simulate the effect of reforestation were USLE cover factor (USLE_C) and curve number (CN2) and their values were assigned by SWAT model.

## 4 Results and discussion

The SWAT sensitive parameters and their calibrated values are shown in Table 3. Fourteen parameters were found to be sensitive for flow and sediment. For transience, the most three sensitive parameters for flow and sediment are curve number (CN2), baseflow alpha factor (ALPHA_BF), and recharge to deep aquifer fractions (RCHRG_DP). The fitted parameters value for CN2, ALPHA_BF, and RCHRG_DP were −0.02, 0.29 and 1.07, respectively. On the other hand, eleven parameters were found to be sensitive for sediment simulation only. The most four sensitive parameters for sediment were linear re-entrainment parameter for channel sediment routing (SPCON), USLE cover factor (USLE_C), exponent of re-entrainment parameter for channel (SPEXP) and channel erodibility factor, (Ch_Erod). The fitted value for USLE_C cover factor varies for different land cover and the assigned values were USLE_C{Dryland-crop}=0.29, USLE_C{Cropland}=0.03, USLE_C{Savanna}=0.17, USLE_C{Grassland}=0.35, and USLE_C{Shurbland}=0.36. The calibrated values for SPCON, SPEXP, Ch_Erod were 0.01, 1.20 and 0.63, respectively.

The SWAT hydrology was calibrated using daily flow from 1990–1996, and validated with data from 1998 to 2003 at El Diem gauging station (Ethiopia-Sudan border). The model performance both for calibration and validation periods were evaluated using the NSE, RSR and PBIAS discussed above, and the results are shown in Table 4. The simulated daily flow matched the observed with NSE, RSR and PBIAS is equal to 0.68, 0.57, and 10%, respectively. During validation period, whereas, the simulated daily flow matched the observed with NES, RSR and PBIAS equal to 0.63, 0.61 and −8%, respectively. According to Moriasi et al. (2007) flow simulation judged as satisfactory if NSE>0.5, RSR≤0.70 and PBIAS=±25%. Thus we found the model performance quite satisfactory both for calibration and validation periods.

A comparison between observed and simulated daily flow for the calibration and validation periods is depicted in Fig. 2. It is worth to notice that the year 2001 is not presented in validation period since the data is missing. The model overestimated rising limb and underestimated recession limb in both calibration and validation periods. The model simulated the peak flow during the calibration periods except the year 1994. However, the model overestimated the peak flow in the validation period. There could be various reasons for the peak miss match but it might be ascribed to input data (e.g. rainfall).

The SWAT sediment simulation part was calibrated from 1990–96 and validated from 1998 to 2003 at El Diem gauging station using daily sediment concentration. It is worth to notice that the sediment concentration data is available only for rainy season that is July to October. The calibration and validation periods model performances for the daily sediment simulation is shown in Table 5. The simulated daily sediment concentration matched the observed for calibration period with NSE, RSR and PBIAS is equal to 0.88, 0.35, and −0.05%, respectively. On the other hand, the daily simulated sediment concentration showed good agreement to the observed with NES, RSR and PBIAS equal to 0.83, 0.61 and −11%, respectively during validation period. Thus we found the sediment simulation performance very satisfactory as compared to the performance range provided as a satisfactory ($NSE>0.5$, $RSR\leq 0.70$ and $PBIAS=\pm 55\%$) by Moriasi et al. (2007). Furthermore, we found our model performance comparable to the recent results reported by Steenhuis et al. (2009) who obtained NSE is equal 0.75 for the calibration and NSE is equal 0.6 and 0.69 for the validation periods at El Diem gauging station.

The comparison between observed and simulated daily sediment concentration for calibration and validation period is shown in Fig. 3. The model well simulated sediment concentration on the rising and the falling limbs of the sediment hydrograph during calibration period. Though, the sediment peak was well mimicked in most of the years, the model underestimated the peaks for 1993 and 1994. In contrast, the validation period overestimated peak concentration except for 1998. The model well simulated the rising limb sediment concentration for whole validation period. On the falling limb, however, the model well simulated the sediment concentration except 2002 and 2003.

Assessment of the spatial variability of soil erosion is interesting for catchment management purposes. The SWAT could be used to locate erosion prone areas and asses the effect of soil conservation measures on sediment yield. Figure 4 shows the relative soil erosion prone areas in the Upper Blue Nile basin. The sub-basins 3 and 8 show extreme soil erosion, whereas severe erosion exhibited in subbasins 4, 5, 13 and 14. Moderate erosion was observed in subbasins 6, 9, 12, 2 and 1 and low erosion proneness was seen in subbasin 10, 15, 11, and 7.

The average sediment yield at the outlet of the Upper Blue Nile was estimated as $117\times10^6\,\mathrm{t\,yr^{-1}}$ for Scenario-0 (existing condition). This result is quite comparable to $140\times10^6\,\mathrm{t\,yr^{-1}}$ estimate by NBCBN (2005) which includes bed load as well. The later approximately accounts for 25% of the total load. However, running the model with different catchment management scenarios provided very interesting results. The implementation of buffer strip (Scenario-1) has reduced the total sediment yield to $66\times10^6\,\mathrm{t\,yr^{-1}}$ at El Diem, equivalent to 44% reduction. The stone-bund (Scenario-2) has reduced the total sediment yield to $70\times10^6\,\mathrm{t\,yr^{-1}}$, equivalent to 41% reduction. Whereas, the reforestation scenario (Scenario-3) has given the least reduction of sediment load ($104\times10^6\,\mathrm{t\,yr^{-1}}$) at El Diem, that is 11% reduction. We found the BMPs efficiency rate on sediment reduction quite within the range as documented in literature (e.g., Vache et al., 2002).

The impact of BMPs at subbasins scale showed wide spatial variability on sediment reduction as is shown in Fig. 5. The sediment reduction was varied from 29% to 68% by buffer strip (Scenario-1), 9% to 69% by stone-bund (Scenario-2) and 46% to 77% by reforestation (Scenario-3). The least reduction for buffer-strip (29%) and stone-bund (10% and 9%) were exhibited by subbasins 3 and 8. Conversely, the reforestation has reduced the sediment yield by 46% in subbasin 3 and 8.

## 5 Conclusions

The SWAT model was applied to identify soil erosion prone areas, assess sediment yield and investigate the impact of three BMPs on sediment reduction from Upper Blue Nile River basin. The model was run daily for 14 yr; calibrated during the period of 1990–96, and validated during the period of 1998–2003 for daily flow and sediment simulation. A daily flow and sediment concentration data monitored at the basin outlet at El Diem gauging station (Ethiopia-Sudan border) was used for calibration and validation. The simulated daily flow showed good agreement to observed with NSE=0.68, RSR=0.57 and PBIAS=10% for calibration and NSE=0.63, RSR=0.61 and PBIAS=−8% for validation. On the other hand, simulated daily sediment concentration well matched the observed with NSE=0.88, RSR=0.35 and PBIAS=−0.05% for calibration and NSE=0.83, RSR=0.61 and PBIAS=−11 for validation. The total sediment yield for existing condition at basin outlet computed to be $117 \times 10^6\,\mathrm{t\,yr^{-1}}$.

The model identified soil erosion prone areas at the hydrological response units, where BMPs (soil conservations measures) were introduced into the model. Specific SWAT parameters were modified to mimic the effect of BMPs on soil erosion, and hence on sediment yield from catchment. The BMPs (buffer-strips, stone-bund and reforestation) type and their parameter values selection were based on documented local research experience.

The results show that the buffer-strips, stone-bund and reforestation have reduced the sediment yield at the outlet of Upper Blue Nile by 44%, 41% and 11%, respectively. While, the reduction of sediment yield at 15 subbasins outlets varied from 29% to 68% by the buffer strip, 9% to 69% by stone-bund and 46% to 77% by reforestation. The quantitative results of this study depends upon the Modified Universal Soil Loss Equation (MUSLE) embedded in SWAT and hence the results may have some limitation (e.g., gully erosion is not represented by MUSLE). Nevertheless, this study clearly demonstrates the efficacy of catchment management intervention (BMPs) for sustainable water resources development in the Eastern Nile basin.

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**Table 1.** Land use/land cover types and area coverage in the Upper Blue Nile.

| Landuse | Description | Area (%) |
|---|---|---|
| Dryland cropland | Land used for agriculture crop | 17 |
| Cropland | Land area covered with mixture of croplands, shrublands, and grasslands | 5.8 |
| Grassland | Land covered by naturally occurring grass | 2.5 |
| Shrubland | Lands characterized by xerophytic vegetative types | 1.1 |
| Savanna | Lands with herbaceous and other understory systems height exceeds 2 m height | 68.8 |
| Deciduous broadleaf forest | Land dominated of deciduous broadleaf trees | 0.02 |
| Evergreen broadleaf forest | Land dominated of evergreen broadleaf trees | 1.6 |
| Mixed forest | Land covered by both deciduous and evergreen trees | 0.7 |
| Water body | Area within the landmass covered by water | 2.2 |
| Barren | Land with exposed rocks and limited ability to support life | 0.4 |
| Residential medium density | Land area covered by structures such as town | 0.2 |

**Table 2.** Scenarios description and SWAT parameters used to represent BMPs.

| Scenarios | Description | SWAT parameter used<br>Parameter name | | Calibration value | Modified value |
|---|---|---|---|---|---|
| Scenario-0 | Baseline | – | | * | * |
| Scenario-1 | Buffer strip | FILTERW | | 0 | 1 (m) |
| Scenario-2 | Stone-bund | SLSUBBSN | 0–10% slope | 61 (m) | 10 (m) |
| | | | 10–20% slope | 24 (m) | 10 (m) |
| | | | >20% slope | 9.1 m | 9.1 (m) |
| | | CN2 | | 81 | 59 |
| | | USLE_P | | 0.53 | 0.32 |
| Scenario-3 | Reforestation | USLE_C | | * | * |
| | | CN2 | | * | * |

* Assigned by SWAT model

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**Table 3.** SWAT sensitive parameters and fitted values.

| Variable | Parameter name | Description | Fitted parameter value |
|---|---|---|---|
| Flow and sediment | CN2.mgt | Curve number | −0.02 |
| | ALPHA_BF.gw | Baseflow alpha factor | 0.29 |
| | GW_DELAY.gw | Groundwater delay time | 215.59 |
| | GWQMN.gw | Threshold water depth in the shallow aquifer | −596.16 |
| | GW_REVAP.gw | Ground water revap co-efficient | −0.46 |
| | REVAPMN.gw | Threshold water depth in the shallow aquifer for revap | 233.24 |
| | ESCO.hru | Soil evaporation compensation factor | 0.58 |
| | RCHRG_DP.gw | Recharge to deep aquifer | 1.07 |
| | CH_K2.rte | Channel effective hydraulic conductivity | 4.22 |
| | SOL_AWC.sol | Available water capacity | 0.54 |
| | SOL_K.sol | Saturated hydraulic conductivity | 0.00 |
| | SURLAG.bsn | Surface runoff lag time | 33.6 |
| | SLSUBBSN.hru | Average slope length | 90.68 |
| | CH_N2.rte | Manning's "n" value for main channel | 0.16 |
| Sediment | USLE_C{Dryland} | USLE land cover factor | 0.29 |
| | USLE_C{Cropland} | Soil erosion land cover factor | 0.03 |
| | USLE_C{Savanna} | USLE land cover factor | 0.17 |
| | USLE_C{Grassland} | USLE land cover factor | 0.35 |
| | USLE_C{Shurbland} | USLE land cover factor | 0.36 |
| | SPCON.bsn | Linear re-entrainment parameter for channel sediment routing | 0.01 |
| | SPEXP.bsn | Exponent of re-entrainment parameter for channel sediment routing | 1.20 |
| | USLE_P.mgt | Universal soil loss equation support practice factor | 0.53 |
| | CH_COV.rte | Channel cover factor | 0.71 |
| | Ch_Erod.rte | Channel erodibility factor | 0.63 |
| | PSP.bsn | Sediment routing factor in main channel | 0.12 |

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**Table 4.** Calibration and validation periods model performance for daily flow simulation.

| Time step | Evaluation method | Calibration | Validation |
|---|---|---|---|
| Daily | NSE | 0.68 | 0.63 |
| | RSR | 0.57 | 0.61 |
| | PBIAS | 10% | –8% |

**Table 5.** Calibration and validation periods model performance for daily sediment simulation.

| Time step | Evaluation method | Calibration | Validation |
|---|---|---|---|
| Daily | NSE | 0.88 | 0.83 |
| | RSR | 0.35 | 0.61 |
| | PBIAS | −0.05% | −11% |

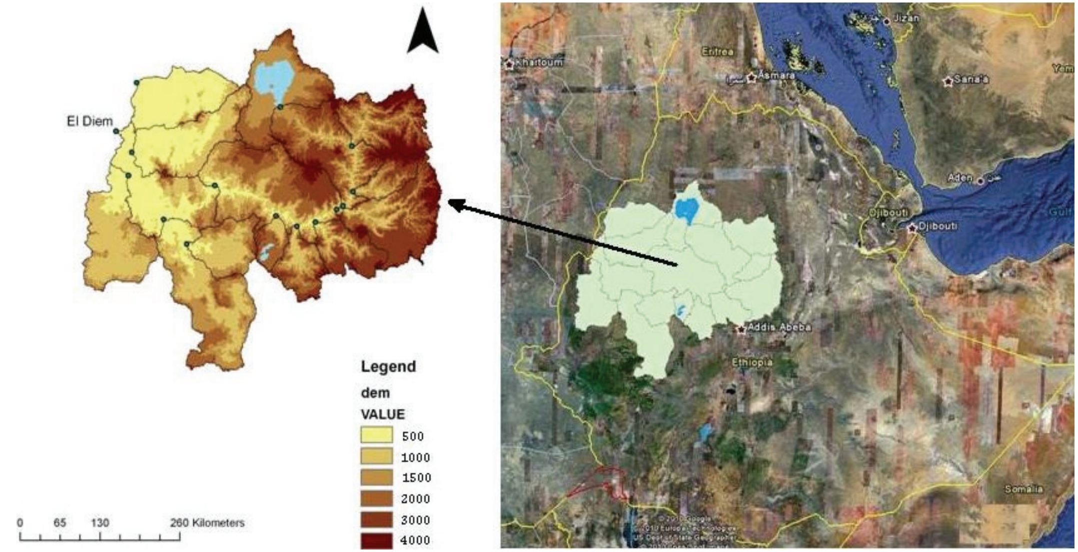

**Fig. 1.** Location map of Upper Blue Nile.

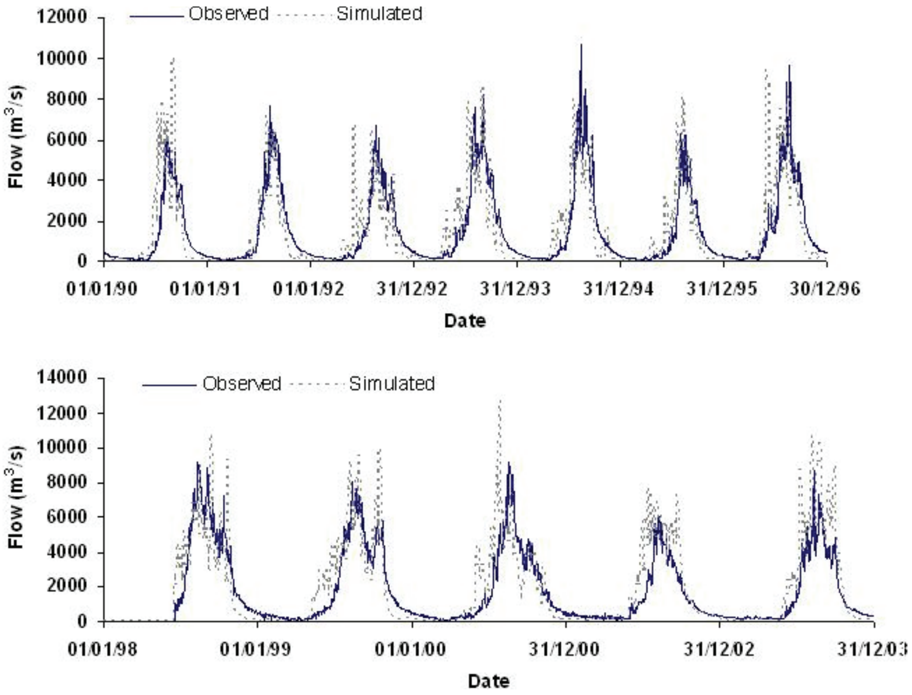

**Fig. 2.** Observed and simulated daily flow hydrographs at El Diem station, calibration (top) and validation (bottom).

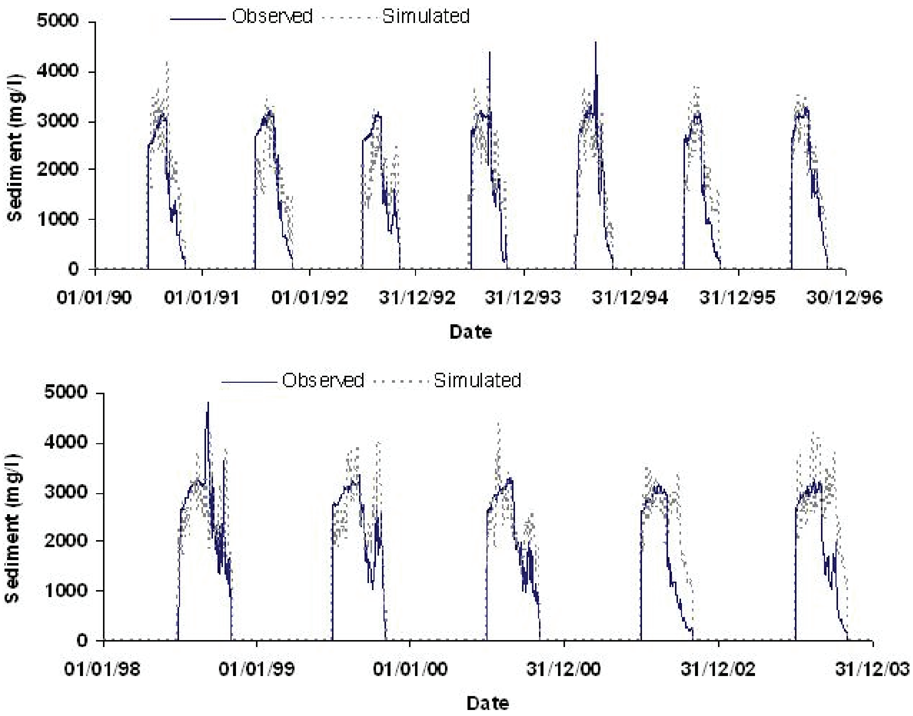

**Fig. 3.** Observed and simulated daily sediment concentration at El Diem gauging station, calibration (top) and validation (bottom).

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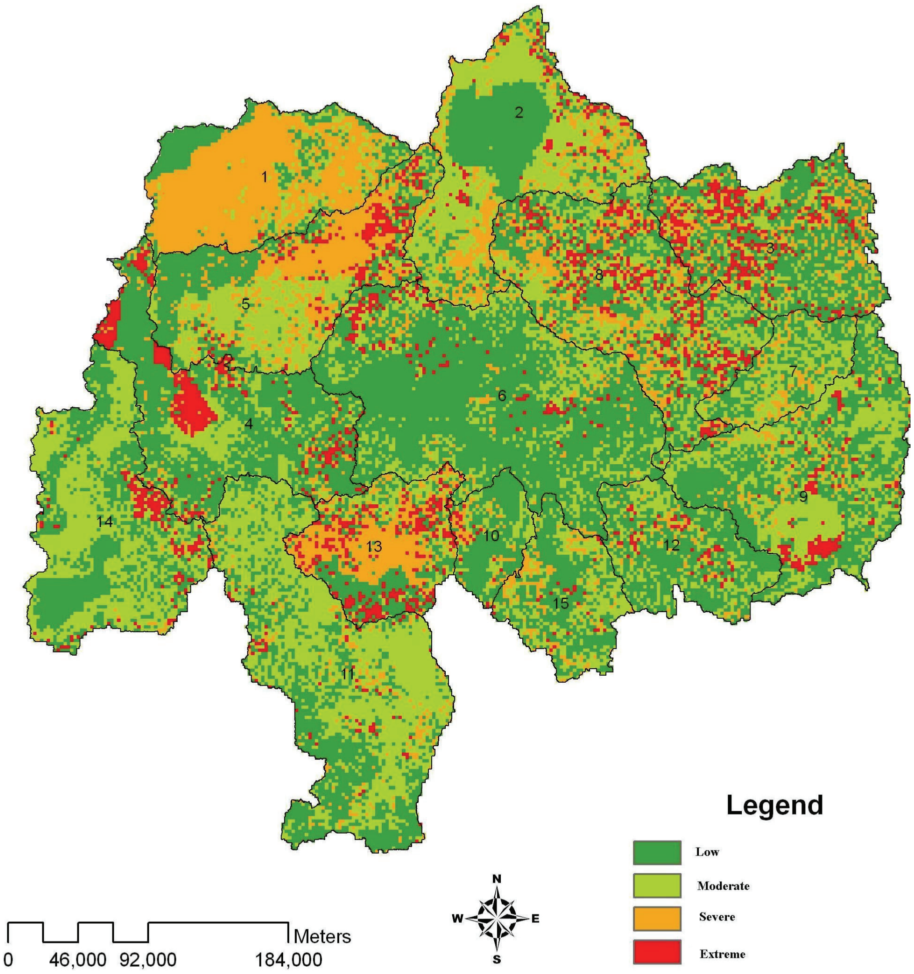

**Fig. 4.** Relative erosion prone area under Scenario-0 in the Upper Blue Nile.

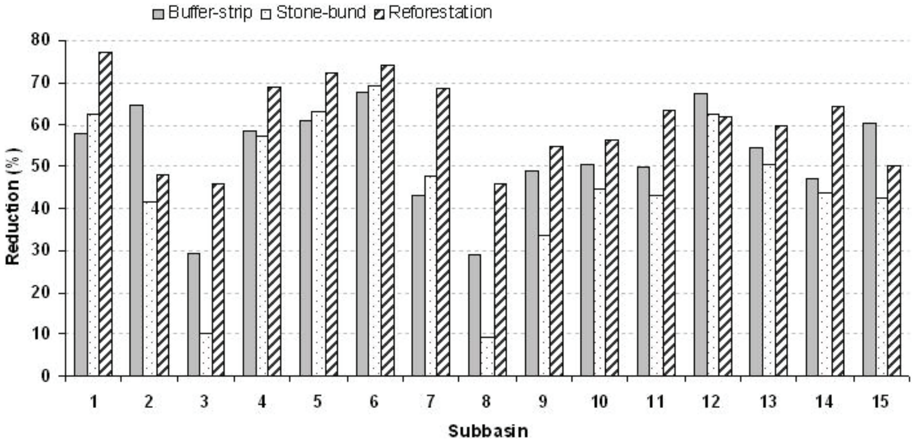

**Fig. 5.** Percent reductions in sediment yield due to BMPs at subbasins level of the Upper Blue Nile basin.