Measuring and modelling the impacts of soil and water conservation measures on soil erosion and sediment yield in North-Western Ethiopian highlands

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Abstract

Although large-scale implementation of SWC measures has been used to reduce soil loss and sedimentation in Ethiopian highlands, no method exists to evaluate how implementation of such measures affect erosion and sedimentary processes. In this study we measured and simulated the impacts of various SWC measures on soil loss and sediment yield using spatially distributed WATEM/SEDEM model calibrated at three sub-watersheds. The methods used comprised of field sampling and monitoring to characterize erosion and sediment yields and GIS analysis to calculate various model input parameters. The measurement and model simulation result showed all SWC scenarios reduced soil erosion and sediment yield and bund structures have reduced erosion by more than 57 to 65%. The integrated use of bund structures, contour cultivation, strip cropping and grass strips (scenario IV), sediment yield was reduced from 44.5 to 8.6 t ha-1 y-1, 30.7 to 5.3 t ha-1 y-1 and 36.6 to 6.3 t ha-1 y-1 in the upper, middle and lower part of Koga catchment respectively. Bund structures and grass strips had the highest specific contribution in controlling soil erosion and sediment yield in both study sub-watersheds. The measured and simulated erosion and sediment yield values were relatively lower at the middle of Koga for scenario I (present-day situation). This might be due to the lower transport capacity and lower sediment connectivity as a result of larger coverage of bunds and subordinate conservation measures such as: traditional diches and diversion channels in Debreyakob. This emphasises the importance of integrated use of conservation strategy to reduce soil erosion and sediment delivery. The calibration of WATEM/SEDEM at sub-watershed level has provided good model performance for measured and simulated erosion and sediment yields. Therefore, WATEM/SEDEM representing the underlying erosion and sedimentary processes can further be used to evaluate the impacts of land use and existing or new SWC scenarios.

1. Introduction

Despite many years of effort to reduce their effects, soil erosion and sedimentation are critical problems in the Ethiopian highlands Bayabil, Tilahun, Collick, Yitaferu, and Steenhuis (2010); (Borselli, Cassi, & Torri, 2008; Nyssen, Poesen, Moeyersons, Haile, & Deckers, 2008; Setegn, Srinivasan, Dargahi, & Melesse, 2009; Taye et al., 2013). Soil erosion causes not only on-site degradation of land resources but also off-site problems such as downstream sedimentation and deposition in fields, plains and water bodies (Hans Hurni, Tato, & Zeleke, 2005; Yeshaneh, Eder, & Blöschl, 2014; Zeleke & Hurni, 2001). Loss of top soil and subsequent silting up of reservoirs degrades the environmental resources necessary for subsistence (Dagnew et al., 2015; P. F. Hudson, 2003; Nyssen et al., 2009; Steenhuis, Winchell, Rossing, Zollweg, & Walter, 1995). This problem extends to downstream countries, Sudan and Egypt, because the Blue Nile drains the Ethiopian highlands and contributes sediment to downstream areas (Bayabil et al., 2010; Nyssen et al., 2008; Setegn, Dargahi, Srinivasan, & Melesse, 2010; Tessema, 2006; Seifu Admassu Tilahun, 2012). To reverse land degradation, the government of Ethiopia launched a massive SWC program for the last three decades (Herweg & Ludi, 1999; Mitiku, Herweg, & Stillhardt, 2006; Shiferaw & Holden, 1998). The interventions were focused on physical SWC strategies with emphasis on reducing accelerated erosion and downstream sedimentation (Desta, 2000; Jemberu, Baartman, Fleskens, Selassie, & Ritsema, 2017; Zeleke & Hurni, 2001). However, sustainable land management (SLM) is not yet attained, with widespread failure of SWC measures (Gebrernichael et al., 2005; Herweg & Ludi, 1999; Tefera & Sterk, 2010).

Ex-ante determination of the effect of SWC strategies on soil erosion and sediment yield can support decision making about SLM (Baptista, Ritsema, Querido, Ferreira, & Geissen, 2015; Nyssen et al., 2008; Setegn et al., 2010). Some studies have indicated that the sediment load is reduced in the Ethiopian highlands by land use changes and widespread use of soil and water management strategies such as bund structures, check dams, flood-control ponds and water diversions (Adimassu, Mekonnen, Yirga, & Kessler, 2014; Gebreegziabher et al., 2009; Gebrernichael et al., 2005; Nyssen et al., 2010; Rust, Corstanje, Holman, & Milne, 2014). However, few measurements are available to quantify the impacts of SWM strategies on soil erosion and sedimentary processes in the Ethiopian highlands, and modelling the linkage of on-site soil erosion rates within a catchment to the sediment yield at the outlet is often lacking due to lack of input data (Adimassu, Kessler, & Hengsdijk, 2012; Grum et al., 2016; Haregeweyn et al., 2013; Nyssen et al., 2008; Steenhuis et al., 1995).

Empirical lumped-approaches have been used to estimate sediment yield using the average basin characteristics such as area, drainage density, slope, land cover, soil type, etc. (Lenzi & Marchi, 2000; Nyssen et al., 2008; Ritsema, Stolte, Oostindie, Van Den Elsen, & Van Dijk, 1996; Setegn et al., 2010; Zhao et al., 2015). However, the validity of the equations resulting from such approaches is limited to the specific areas for which they have been established (Feng, Wang, Chen, Fu, & Bai, 2010; Haregeweyn et al., 2008; Quiñonero-Rubio, Nadeu, Boix-Fayos, & Vente, 2016). Inherent to lumped approaches is that it is not possible to take into account the spatial structure of land use and topography within the catchment on erosion and sediment delivery (de Vente & Poesen, 2005; Haregeweyn et al., 2008; Seifu A Tilahun et al., 2015). This inherently limits their applicability to practical problems such as the evaluation of different SWC measures on soil erosion and sediment delivery (A. J. Van Rompaey, Verstraeten, Van Oost, Govers, & Poesen, 2001; Vandaele & Poesen, 1995; Zabaleta, Martinez, Uriarte, & Antiguedad, 2007). Likewise, the sediment yield measured at gauging stations of many river systems is only a fraction of the total sediment load delivered to reservoirs and dams in the downstream areas (Adimassu et al., 2014; N. E. Asselman, 1999; Bayabil et al., 2010; de Vente, Poesen, Bazzoffi, Rompaey, & Verstraeten, 2006; Haregeweyn et al., 2008). These problems can be overcome by using a spatially distributed model, whereby the eroded sediment is explicitly routed over the landscape towards the river system, allowing the evaluation of the effect of SWC measures on erosion and sedimentation processes (Romero-Diaz, Alonso-Sarria, & Martinez-Lloris, 2007; Vandaele & Poesen, 1995; Wudneh, Erkossa, & Devi, 2014; Zabaleta et al., 2007; Zhao et al., 2015).

Spatially distributed models have been applied globally to support SWC decisions (Betrie, Mohamed, van Griensven, & Srinivasan, 2011; Boix-Fayos, de Vente, Martinez-Mena, Barbera, & Castillo, 2008; Fleskens & Stringer, 2014; Haregeweyn et al., 2013; Lemann et al., 2016b). The spatially distributed Water and Tillage Erosion / Sediment Delivery Model (WATEM/SEDEM) provides estimates of long-term mean annual soil erosion rates and sediment yield (Van Oost et al., 2005; A. Van Rompaey, Bazzoffi, Jones, & Montanarella, 2005; A. J. Van Rompaey et al., 2001; Verstraeten, Prosser, & Fogarty, 2007). Haregeweyn et al. (2013) used WATEM/SEDEM to assess sediment yield in Tigray region, Northern Ethiopia. Didone, Minella, and Evrard (2017) applied WATEM/SEDEM for evaluating the impact of SWC scenarios in southern Brazil. In SE Spain, WATEM/SEDEM was used to assess the impacts of check dams, land use change and forest restoration on sediment yield Quinonero-Rubio et al. (2016).

Validation of the spatial pattern of erosion and sediment connectivity within the (treated) catchment is complicated and accurate prediction of sediment yield at outlets of sub-watersheds does not mean that the spatial patterns of erosion and sediment yields are also accurately predicted (Bracken, Turnbull, Wainwright, & Bogaart, 2015; Marchamalo, Hooke, & Sandercock, 2016). However, by simulating the spatial distribution of erosion, transport capacity, sediment routing and sediment deposition, the effects of SWC measures can be spatially evaluated (Feng et al., 2010; Quinonero-Rubio et al., 2016). In modelling SWC measures, the routing algorithms can alter the transport capacity and sediment deposition patterns, while causing little change in predicted total erosion and sediment yield (Takken et al., 1999; Takken et al., 2005; Vigiak, Sterk, Romanowicz, & Beven, 2006).

Based on previous experiences (Haregeweyn et al., 2013), the successful calibration of WATEM/SEDEM could be further used for evaluating of the effect of SWC measures on soil erosion and sediment delivery in the Ethiopian highlands. In this study, WATEM/SEDEM was applied to simulate the effect of alternative SWC scenarios at sub-watershed level to identify critical sediment source areas or erosion hotspots and to evaluate the effect of SWM strategies on soil erosion and sediment delivery. The objectives of the present study were: (1) to quantify the spatial distribution of soil erosion and sediment delivery at sub-watershed scale; (2) to evaluate the effect of different SWC measures on soil erosion and sediment yield and (3) to determine the most effective set of SWC strategies using scenario analysis.

2. Materials and methods

2.1 Study area

Koga catchment is located south of Lake Tana, at the source of the Blue Nile, in the highlands of North-Western Ethiopia ($37^0$02" - 37^0 17" E longitude, $11^0$10" - 11^0 25" N latitude; Figure 1). The Koga catchment is a narrow and elongated catchment, which has a concentrated networks of water divides, with highly variable and rugged topography. The total area of the catchment is 230 km^2 with elevations ranging from 1860 to 3128 m a.s.l. In this catchment, the annual rainfall pattern is unimodal and rainfall mostly occurs between June and September. The average annual temperature and rainfall are 18.4°C and 1480 mm, respectively. Approximately 86% of Koga catchment is cultivated land, while around 12% is forest and the remaining part fallow and grazing land. Koga catchment represents a typical Ethiopian sub-humid highland environment where SWC measures have been implemented on a massive scale to reduce the effect of soil erosion and sedimentation in downstream areas and reservoirs (Mekonnen, Keesstra, Baartman, Ritsema, & Melesse, 2015). Three study sub-watersheds, Asanat, Debre Yakob and Rim, with drainage areas of 755, 303 and 1010 ha, were respectively selected at the upper, middle and lower reaches of Koga. Asanat is a hilly environment where more than 55% of the area has slopes of 15%-30% and ˜11% of the area has slopes greater than 30%. In Debre Yakob 32% of the area has slopes of 15%-30% and about 33% of the area has slopes of less than 10%. Rim sub-watershed is relatively flat with 85% of the area having slopes of less than 10%. Approximately, 72% of Asanat, 64% of Debre Yakob and 72% of Rim is cultivated land while around 12%, 18% and 55% is used for grazing in Asanat, Debre Yakob and Rim respectively. The study sub-watersheds drain to Koga river which in turn drains into Lake Tana. The soil types in Koga are classified as Leptosols, Luvisols, Nitosols, Vertisols and Fluvisols. At the lower elevations of the catchments, Luvisols are the dominant soil type; these areas are well-suited for agricultural production. Leptosols are the predominant soil type in the upper part of the catchments; these soils are less suitable for crop production.

Fig. 1 approximately here

2.2 Field sampling and measurements

Rainfall and stream discharge were automatically measured at the outlets of study sub-watersheds at 10-minutes intervals using Hobo data logger rain gauges and pressure transducer divers, respectively for periods 2016-2017. Thus stream discharge was estimated from depth measurements using rating curves calculated from the monitoring diver stations (Jemberu et al. sub.). One-litre SSC samples were taken manually for all rainfall events during the rainy season of 2016 and 2017. Sampling during a rainfall event started when the discharge developed and when the water at each outlet looked brown. About 3-8 representative samples were taken for each rain event based on fluctuation of flow depth. Due to large discharge, it was often impossible to sample sediment from an entire water column. However, since the flow was very turbulent during those events, a good mixing of sediments was observed from the brown colour of storm water for the rising and receding limbs of the flood so we assumed samples were representative for the full water column. Each sample was filtered using Whatman filter paper with a pore opening of 2.5 µm, oven dried and weighted to allow determination of dry sediment mass. A total of 101 one-litre samples for Asanat, 98 for Debre Yakob and 105 for Rim were taken during the rainy seasons of 2016 and 2017. The sediment yield (SY), in tonnes per day, for the stream's cross-section was then obtained by multiplying the concentration, C (g/l) by the discharge Q (m^3/s) (N. Asselman, 2000; Moliere, Evans, Saynor, & Erskine, 2004; Morehead, Syvitski, Hutton, & Peckham, 2003).

SY = C * Q * 86.4 (1)

Where 86.4 is a factor to convert to ton/ha.

2.3 WATEM/SEDEM model description

The WATEM/SEDEM model was developed to predict sediment yield for different catchment scales with limited data requirements (Van Oost, Govers, & Desmet, 2000; A. J. Van Rompaey, Govers, & Puttemans, 2002; A. J. Van Rompaey et al., 2001). WATEM/SEDEM is a sediment delivery model that calculates how much sediment is transported to the river channel on an annual basis (Van Oost et al., 2000; A. Van Rompaey et al., 2005; A. J. Van Rompaey et al., 2001). It is a spatially distributed model; for each grid cell, mean annual soil erosion and mean annual transport capacity are calculated (Van Oost et al., 2000; A. J. Van Rompaey et al., 2001; Verstraeten, Oost, Rompaey, Poesen, & Govers, 2002). WATEM/SEDEM comprises of soil erosion and sediment transport capacity assessment, and sediment routing processes (Van Oost et al., 2000; A. J. Van Rompaey et al., 2001). The model enables exploring the spatial pattern of sediment sources, erosion hotspot areas and annual sediment delivery. The effect of various existing or new SWC measures can be evaluated by the way they impact on spatial patterns, rates and processes of soil erosion (Didoné et al., 2017; A. J. Van Rompaey et al., 2002).

The model calculations are based on a spatially distributed assessment of mean annual soil erosion using the Revised Universal Soil Loss Equation (RUSLE) and mean annual sediment transport capacity (TC) (de Vente, Poesen, Verstraeten, Van Rompaey, & Govers, 2008; Desmet & Govers, 1996; A. Van Rompaey et al., 2005; Verstraeten & Poesen, 2000, 2001). An adapted version of the RUSLE (Renard, 1997) is used:

SE = R * K * LS (i, j) * C * P (2)

Where:

SE = Mean annual soil loss (kg $m^{-2}y^{-1}$)

R = Erosivity factor (MJ mm $m^{-2}h^{-1}y^{-1}$)

K = Erodibility factor (kg h $MJ^{-1}mm^{-1}$)

LS (i, j) = Two-dimensional slope gradient and slope length factor of (i, j) coordinates

C = Crop management factor

P = Erosion control factor

The two dimensional slope length and steepness factor LS (i, j) were calculated based on an algorithm proposed by Desmet and Govers (1996):

$LS(i,j) =[(Ai,j+D^2)^{m+1}-A(i,j)^{m+1}(6.8Sg(i,j)^{0.8})]/D^{m+2}X(i,j)^m(22.13)^m$(3)

$X(i,j) =\sin\alpha(i,j)+\cos\alpha(i,j)$ (4)

Where:

A(i, j) is the runoff contributing area at the inlet of a grid cell (m^2); D is the length of the side of a grid cell (m); Sg (i,j) is the slope gradient of the grid cell (i.j); α(i,j) is the aspect of the grid cell (i,j); and m is the slope length exponent.

This two-dimensional approach of the RUSLE not only accounts for inter-rill and rill erosion but also for smaller ephemeral gullies as the effects of flow convergence are explicitly accounted for (Desmet & Govers, 1996).

2.3.1 Transport capacity and sediment routing

Transport capacity (TC) is the maximum potential sediment that can exit down slope of a grid cell per unit length (kg m^{-1}). For each cell in arable and non-arable land use types, different TC values were considered and the original TC which considers the transport capacity as a function of potential rill and interrill erosion was used in this study (Van Oost et al., 2000; A. J. Van Rompaey et al., 2002; A. J. Van Rompaey et al., 2001).

$TC = KTC * R * K * (LS(i,j) - 4.1S_{IR})$ (5)

Where:

TC = Transport capacity (kg m^{-1} y^{-1})

KTC = Transport capacity coefficient (m)

S_{IR} = inter-rill slope gradient (mm^{-1})

KTC describes the proportionality between the potential for rill erosion and TC. It can be interpreted as the theoretical upslope distance that is needed to produce enough sediment to reach the TC at the grid cell, assuming a uniform slope and runoff discharge.

The inter rill slope gradient is calculated based on Govers and Poesen (1988) as follows.

$S_{IR} = 6.86S^{0.8}$ (6)

Where: S is slope gradient (m m^{-1})

WATEM/SEDEM employs a routing algorithm to transfer the eroded sediment from the source to the river network using a multiple flow algorithm (Desmet & Govers, 1996; Haregeweyn et al., 2013; A. J. Van Rompaey et al., 2001). The original TC equation (Equation 5) allows the model to represent gully erosion through flow concentrations and preferential channel pathways connected with rivers (A. J. Van Rompaey et al., 2001; Verstraeten et al., 2007). The routing algorithms in treated catchment areas can alter the TC and sediment deposition patterns, while causing little change in predicted total erosion and sediment yield (Takken et al., 1999; Takken et al., 2005; Vigiak et al., 2006). Thus, following the flow path, the sediment is transferred downslope if the local transport capacity is higher than the incoming sediment volume. If the transport capacity is lower than the incoming sediment volume, sediment deposition occurs. The output of the model consists of a map indicating the amount of soil erosion or deposition at each pixel depending on transport capacity.

To investigate sediment connectivity, a sediment delivery ratio (SDR) approach that takes into account the spatial distribution of gross erosion and deposition processes was used, as suggested by Atkinson (1995); Ferro, Di Stefano, Giordano, and Rizzo (1998). Hence, attempts to model connectivity have been made by studying the SDR in order to accommodate gross erosion estimate of soil loss to values observed at a catchment outlets (Ferro & Porto, 2000; A. J. Van Rompaey et al., 2001) as follow:

$SDR = SY/E$ (7)

Where,

SDR = the sediment delivery ratio

SY = sediment yield

E = gross erosion per unit area

2.3.2 WATEM/SEDEM input data

The rainfall erosivity factor (R) was derived from the relationship between annual rainfall and annual erosivity expressed in MJ mm m^{-2} h^{-1} y^{-1}. R expresses the aggressivity of rainfall and kinetic energy (KE) is generally suggested to indicate the ability of a raindrop to detach soil particles from a soil mass (Nearing et al., 2005; Renard, 1997). R was calculated using the following formula proposed by Nearing et al. (2005); Renard (1997):

$$R=\frac{\sum_{i=1}^{j}(E*I30)i}{N} \quad (8)$$

Where,

E = the total storm energy (MJ)

I_{30} = the maximum 30-minute intensity (mm h^{-1}) of daily rainfall i,

j = the number of rain events in an N year period

N = the number of observation years.

Total storm energy was determined using:

$$E = 1.213 + 0.89 \log I \quad (9)$$

Where,

E = is kinetic energy of each rainstorm KJ $m^{-2}mm^{-1}$

I = is average intensity of daily rainfall i.

The erodibility (t h MJ^{-1} mm^{-1}) of the soil was calculated from soil properties using the following equation proposed by N. Hudson (1993); Renard (1997); Wischmeier and Smith (1978):

$$K = [(2.1 * 10^{-4} M^{1.14} (12\text{-}OM)) + 3.25 (S\text{-}2) + 2.5 (P\text{-}3)] / 7.59 \quad (10)$$

Where,

M (the textural factor) = (%silt + %sand) * (100 - %clay);

OM= % organic matter

S and P are field-determined average values of aggregate structure and permeability classes described as follows:

S = Aggregate/structural class with values (1-4): 1 for very fine, 2 for fine, 3 for medium coarse, 4 for massive structure respectively, and

P = Permeable class with values (1-6)]: 1 for fast, 2 for fast to moderate, 3 for moderate, 4 for low to moderate, 5 for low, and 6 for very low permeability respectively.

The remaining RUSLE parameters, crop management (C) factor and erosion control factor (P) factor, were consulted from the literature (H Hurni, 1985; Renard, 1997). Annual values of the C-factor were determined based on the land use types defined by a previous study (H Hurni, 1985), and spatially attributed based on the current land cover (Renald, 1997). The P–factor values were determined based on the types of SWC measures implemented in different areas (Table 1). The P-factor represents the ratio of soil loss with conservation measures to a reference plot without conservation measures: a value of one refers to a cultivated land without conservation practice.

Table 1 approximately here

The P-factor considers the interaction of LS (i,j) attributes and vegetation cover (C-factor), as well as the direction of flow and TC, which depends on the type and effectiveness of physical conservation measures (Foster, 2002; Renard, 1997). Therefore, P–factor and C-factor values were used in the WATEM/SEDEM model to verify the responses of different SWC scenarios to soil erosion and sediment yield in the study sub-watersheds. The P-factor values for the different supporting conservation practices were adoptable to local study sites environmental contexts (Foster, 2002; Renard, 1997; Wischmeier & Smith, 1978) and thus the compounding P-factor for different scenarios of SWC measures were calculated as follows:

$P = P_B * P_{CC} * P_{SC} * P_{GS}$ (11)

Where P_B, P_{CC}, P_{SC} and P_{GS} are conservation practice sub-factors for bund structures, contour cultivation, strip cropping and grass strips respectively (Table 1). The Parcel trap efficiency in WATEM/SEDEM, Ptef, refers to the way each pixel's runoff contribution to the upstream contributing area is reduced. This means that for different land use types, less runoff is simulated, thereby decreasing downstream LS (i,j) values and erosion rate by Ptef (Van Oost et al., 2000; A. J. Van Rompaey et al., 2001). Ptef values of 10 for cultivated lands and 75 for pasture and forests were chosen based on the optimal or KTC(h) during model calibration.

A DEM with 20m resolution was derived from global SRTM topographic data by resampling 30 m resolution and the land use map was created from Landsat GLSTM_2000 image. Besides, a parcel map was created by the model by combining the DEM, stream, road, forest, arable land, pasture and catchment area delineations to account for the effect of landscape structure on soil erosion and sedimentation processes (Van Oost et al., 2000). A parcel map is a reclassified land use map that takes a distinction between, arable land, forest, pasture, roads, infrastructures, rivers and build-up areas. This makes it possible to incorporate the effect of field borders on runoff diversion, runoff interception, erosion and sediment deposition (A. Van Rompaey, Krasa, & Dostal, 2007; A. J. Van Rompaey et al., 2001).

2.4 SWC scenarios

The SWC scenarios evaluated in this study were developed based on a biophysical inventory, farmers' perception (Jemberu, Baartman, Fleskens, & Ritsema, 2018) and the regional government's five year strategy program in the study sub-watersheds to select promising conservation strategies. Three conservation strategies, including physical (bund structures), agronomic (strip cropping and contour cultivation) and vegetative (grass strips) measures were created for the three sub-watersheds of Koga catchment to determine where each type of or combination of SWC measures can be implemented. Consequently, soil erosion, sediment deposition and sediment yields were simulated for five alternative scenarios of SWC measures described as follows. Scenario I: a baseline condition (present-day situation) including existing bund structures; Scenario II: existing bund structures and contour cultivation; Scenario III: combination of bunds, contour cultivation and strip cropping; Scenario IV: integrated use of bunds, contour cultivation, strip cropping and grass strips; and Scenario V: a scenario without SWC practices (Table 2).

Table 2 Approximately here

2.5 Model calibration

We calibrated and validated WATEM/SEDEM for this study based on sediment yields measured at the three study sub-watersheds of Koga catchment from 2016 to 2017. The sediment yield data of 2016 was used for calibration and that of 2017 to validate the performance of the model. The model was calibrated based on area-specific and absolute sediment yield (by minimizing the difference between measured and simulated values) since the objective of the study was to assess the effect of SWC measures on soil loss and sedimentary processes for various SWC scenarios at sub-watershed level. The model was first calibrated for the baseline scenario (scenario I) by changing the maximum and minimum values of the KTC or KTC (h) and KTC (l). The model was sensitive to KTC (h) and less sensitive to KTC(l) whereas the model was insensitive to the threshold KTC(t) value. The KTC(t) was set at 0.1 for arable and 0.01 for non-arable land uses for all sub-watersheds. After calibration, the model was run for the four remaining SWC scenarios.

The Nash-Sutcliff efficiency (NSE) statistic was applied to evaluate the efficiency of the model. NSE is a normalized statistic determining the relative magnitude of residual variance (between predicted and observed values) compared with the measured data variance. NSE values between 0 and 1.0 demonstrate model efficiency; the closer the value of NSE approaches 1, the more efficient is the model. A satisfactory model should have NSE >0.50 (Baartman, Jetten, Ritsema, & Vente, 2012). The accuracy of the model in predicting soil erosion for these scenarios was also assessed qualitatively by relating to previous studies on soil erosion (Jemberu et al., 2018) and available literature for similar areas (Bewket & Sterk, 2003; Herweg & Ludi, 1999; Mitiku et al., 2006; Nyssen et al., 2010).

3. Results and discussions

3.1 Model calibration and validation results

In Rim sub-watershed, KTC(h) values of 350 and KTC(l) 75 delivered optimal model performance, whereas a KTC (h) value of 250 and KTC(l) value 25 were optimal in Asanat and Debre Yakob sub-watersheds. The observed and predicted sediment yields were 35.6 and 36.1 t ha^{-1} y^{-1} for Asanat, 24.4 and 25.1 t ha^{-1} y^{-1} for Debre Yakob and 31.7 and 32.5 t ha^{-1} y^{-1} for Rim respectively, with corresponding NSE values of 0.81 in Asanat, 0.56 in Debre Yakob and 0.72 in Rim at optimal values of KTC(h) (Figure 2). Generally the model over-predicted sediment yield in all sub-watersheds (Table 3). This may be partially attributed to considerable effects of SWC measures on soil erosion and transport capacity (Haregeweyn et al., 2013; A. Van Rompaey et al., 2005). The majority of cultivated lands of the study sub-watersheds are treated with bund structures. Although bunds had variable spacing, a routing algorithm was used for all bunds by creating a specific parcel map layer for all bunds. The model showed relatively higher performance in Asanat sub-watershed. This is likely due to a well-defined parcel map layer, and LS (i.j) and flow routing algorithm as a result of narrow and uniform spacing of bunds compared to Rim and Debreyakob. The parcel connectivity in each pixel, Ptef and P-factor, which together adjust the effect of bunds on erosion, accurately represent the situation on the ground in Asanat.

Fig. 2 approximately here

Table 3 approximately here

3.2 The effect of SWC measures on rate and patterns of soil erosion

The net soil erosion maps as calculated by WATEM/SEDEM for the three study sub-watersheds are given in Figures 5.3-5.5. The mean annual soil erosion rate calculated from the sum of mean annual sediment production and sediment deposition simulated by WATEM/SEDEM for the study watersheds are given in Table 4. The simulated soil erosion indicates high spatial variation in all study sub-watersheds.

Table 4 approximately here

The results of the model with SWC scenarios show a progressive decrease in soil erosion, indicating a considerable effect of SWC measures. When comparing the present-day situation (scenario I) with a situation without SWC measures (scenario V), simulated soil erosion is more than 57% lower in Asanat, 65% in Debre Yakob and 53% in Rim sub-watersheds. In scenario II (bunds and contour cultivation), erosion rates were further decreased by 8% in Asanat, 10% in Debre Yakob and 15% in Rim with respect to current conditions. In scenario III, 5% less erosion was observed in Asanat, 12% less in Debre Yakob and 14% less in Rim compared to scenario II. The largest reduction of soil erosion was simulated for scenario IV in all study sub-watersheds (Table 4). In scenario IV (combination of bunds, contour cultivation, strip cropping and grass strips), soil erosion was decreased by 128, 164 and 180% in Asanat, Debre Yakob and Rim, respectively, when compared to scenario V (no SWC measures) and by 45, 61 and 83 % when compared to scenario I (present situation).

Fig. 3 approximately here

Soil erosion was reduced by a higher percentage in Debre Yakob than for Asanat and Rim when comparing the present day situation to a scenario where sub-catchments would be untreated (scenario V). This may be due to a larger coverage of bund structures and other conservation measures such as traditional ditches, diversions and check dams in Debreyakob. Relatively, contour cultivation, strip cropping and grass strips were more effective in reducing soil erosion in Rim compared to Debre Yakob and Asanat (Table 4). This is most likely due to the topographic characteristics in Rim. On steeper slopes, agronomic measures such as contour cultivation and strip cultivation are less effective in reducing soil erosion. Although soil erosion and/or sediment yield is reduced in the present-day situation (scenario I) as compared with a 'no SWC measures' situation (scenario V), in most parts of the cultivated lands of the study sub-watersheds still high rates of erosion were simulated. This emphasises the requirement to combine various conservation strategies to reduce soil erosion and sediment delivery in the study sub-watersheds. From the analysis of the present-day situation, the erosion map suggests that areas with greatest soil erosion are concentrated on locations with steep slopes and/or areas with poor bund structures (smaller dimensions and wider spacing). Lower erosion rates in intervention scenarios II-IV correspond to areas treated with effective bund structures, including upgrading of the stability of bund structures. Extremely high erosion rates (>66 t ha^{-1}) were observed over large parts of cultivated lands in Asanat whereas higher deposition areas were concentrated in Debre Yakob and in the downstream part of Rim (Figure 3-5).

Fig. 4 approximately here

Comparison of these model results with the range of soil erosion rates reported for cultivated lands treated with SWC measures shows generally good agreement. The model predicts reasonably acceptable ranges of soil erosion as compared to annual soil loss observed in treated farm plots in previous studies in similar areas in the Ethiopian highlands (Bewket & Sterk, 2003; Mitiku et al., 2006). Herweg and Ludi (1999) estimated an average soil loss reduction of 40% by graded soil bunds and 50% reduction with fanyajuu bunds in Anjeni, Ethiopian highlands. Another study in Tigray, Northern Ethiopia by Vancampenhout et al. (2006) found that stone bunds trapped 64% of soil otherwise lossed by soil erosion.

Fig. 5 approximately here

Simulation of the effect of physical SWC measures (bunds and diversion channels) on sediment yield with the Soil and Water Assessment Tool (SWAT) in the upper blue Nile basin by Lemann et al. (2016a) estimated an average sediment yield reduction of 54% while Dagnew et al. (2015) found a 57% decrease in suspended sediment concentration (SSC) at Debremewi sub-watershed in NW Ethiopian highlands. A similar study in Kenya reported by Hessel and Tenge (2008) show that LISEM-simulated physical SWC scenarios decreased erosion by 60% in an agricultural catchment. Subhatu et al. (2017) estimated 32-37 t ha^{-1} y^{-1} soil loss using the USLE in treated catchment of Minichet, North Ethiopian highlands.

The estimate made on impacts of SWC measures in this study also agrees well with another model-based soil erosion estimation for treated catchments by Hessel, Messing, Liding, Ritsema, and Stolte (2003) where soil loss was decreased by 60% by simulating the impacts of SWC measures using LISEM (Limburg Soil Erosion Model). Nyssen et al. (2007) estimated a 0.32 conservation practice P-factor for bund structures in USLE and estimated soil loss rates of 58 t $ha^{-1}y^{-1}$ in the Tigray region of Northern Ethiopia. In a related study, Nyssen et al. (2006) investigated the effects of SWC measures using the WOFOST and LISEM models for Tigray and found a 68% reduction of soil erosion due to bund structures. In their assessment of landscape susceptibility to soil erosion using a GIS-based approach in North Ethiopia, Tamene, Adimassu, Aynekulu, and Yaekob (2017) predicted a mean annual soil loss of 45 t $ha^{-1}y^{-1}$ using RUSLE for treated cultivated lands.

The large variation in predicted erosion rates across the study sub-watersheds reflects the high spatial variation of factors potentially influencing soil erosion. The effect of SWC measures on soil erosion was not uniform for the same land use types and slope classes. This emphasises that the effectiveness of SWC measures on controlling erosion depends on biophysical factors such as topography, land use and geology, etc. Furthermore, the spatial pattern and type of land use are relevant to erosion because changes in land use can alter the efficiency of SWC measures to control soil erosion within sub-watersheds (Desmet & Govers, 1995). Roads, field boundaries and other landscape structures also affect the efficiency of SWC measures to prevent soil erosion and sedimentation between various land units (A. J. Van Rompaey et al., 2001). This effect is well accounted in WATEM/SEDEM by incorporating a parcel map (A. J. Van Rompaey et al., 2001). The spatial variation of various conservation scenarios clearly indicates the importance of landscape modification by the use of physical SWC measures on soil erosion. The primary purpose of SWC measures is to divide the natural length of the hill slope into smaller sections so that runoff and soil erosion are reduced (Troeh, Hobbs, & Donahue, 1980) and this process is determined mainly by topographic characteristics and land use (Meshesha, Tsunekawa, Tsubo, & Haregeweyn, 2012). Meshesha et al. (2012); Nyssen et al. (2007) reported high variation in soil loss rates in plot experiments and catchment scale modelling, confirming the strong spatial variability and scale dependency of soil erosion processes due to various attributes of catchment areas.

Previous studies in the Ethiopian highlands suggest that bund structures reduce soil erosion; however, the effectiveness of these measures can be improved by integrated use of physical, agronomic and vegetative conservation strategies at sub-catchment level (Betrie et al., 2011; Dubale, 2001). Nyssen et al. (2007) indicated that the use of one or a combination of SWC measures depends on the objective and economic viability of conservation strategies. According to the plot experiments of Amare et al. (2014), the combined use of soil bund structures with Tephrosia plantation (a biological SWC measures) in the North-western Ethiopian highlands on average decreased soil loss by 71 to 26 t ha^{-1} y^{-1}. An additional benefit of the biological SWC measures reported by Amare et al. (2014) was that 2.8 t ha^{-1} y^{-1} of dried forage was obtained from elephant grass grown on bund structures. Thus, the biomass obtained could compensate the land taken out of production by physical structures (8-10%) and could alleviate the shortage of animal feed (Adimassu et al., 2012). In addition, the soil organic matter content is enhanced by integrated use of biological conservation strategies and bunds (Amare et al., 2014).

3.3 Impacts of SWC measures on sediment connectivity and yield

This study illustrates that sediment deposition and yield were highly variable within study sub-watersheds. This is most likely due to the effect of SWC measures as well as biophysical characteristics such as topography, land use and soil types (Grum et al., 2017; Mekonnen et al., 2015). However, previous studies indicated that specific sediment yield decreases with increase in catchment area (de Vente, Poesen, Arabkhedri, & Verstraeten, 2007; Descheemaeker et al., 2006). According to Grum et al. (2017); Haregeweyn et al. (2008), the lower rate of specific sediment yield in larger watersheds is due to increased sedimentation processes and sinks at obstructions in the lower reaches of larger watersheds. Even though the topography is less steep, the SDR was very high in Rim sub-watershed reaching up to 56% (Table 5). This might be due to natural ditches, stream bank erosion and gullies which increase sediment connectivity. Rim sub-watershed is severely affected by landslides and gully erosion (Jemberu et al., 2018). In line with this, Verstraeten et al. (2002) reported that areas where surface runoff is concentrated in ditches and gullies facilitate sediment delivery and high TC and SDR. A large part of landscape becomes connected to the stream by continuous paths of concentrated overland flow and channel flow from gullies (Gallart, Llorens, & Latron, 1994).

This study demonstrates that the measurement of sediment yield at the outlet of catchment areas, taking into account the spatial distribution of total erosion and deposition processes, can be a good indicator of erosion taking place within the upland areas. However, in catchment areas with low TC and SDR, the measurement of sediment yield at the outlets of the catchment areas can be a poor indicator for erosion processes in the upland catchment areas. Overall connectivity within catchment areas varies with all sediment production, transfer and delivery processes that occur within it (Borselli et al., 2008). Therefore, catchment areas with high soil erosion are not necessary areas contributing most sediment to rivers (Stall, 1985; Steegen et al., 2000; Verstraeten et al., 2002). According to Cammeraat (2002), surface roughness, vegetation cover and rain intensity influence sediment production, transport from the upper part of the catchments and delivery to the river channels. The differences in sediment connectivity and yield between study sub-watersheds were apparently due to the effects of conservation measures and topographic characteristics. In addition the morphology and channel incision also controlled sediment connectivity and yield. The impact of a given type of impediment of sediment flow depends upon its size and position in the catchment area (Fryirs, Brierley, Preston, & Kasai, 2007). Moreover, the sediment detachment, transfer and delivery to the river channels not only dependent on overall biophysical characteristics of catchment areas such as land cover, topography and geology, but also on the effects of watershed development activities (Grauso, Pasanisi, & Tebano, 2018).

Table 5 approximately here

The large heterogeneities in TC and SDR in the study sub-watersheds may reflect topographic characteristics and the spatial pattern and effect of conservation measures implemented in the study sub-watersheds. In line with this, Einstein (1950); Verstraeten et al. (2002) reported that sediment flows are highly variable with the topographic characteristics and land use types. Earlier work by Einstein (1950); Stall (1985) showed that factors influencing soil loss and TC across catchment areas have implications for sediment connectivity and sediment yield. Marchamalo et al. (2016), in their study of sediment connectivity as a framework for understanding sediment transfer at multiple scales in SE Spain, emphasises that land use and SWC measures have a clear impact on sediment connectivity, by affecting the link between the sediment produced on the upper side of the catchment and transporting to streams. The Water Availability in Semi-Arid Environments with Sediment Dynamics Component (WASA-SED) model simulation by Medeiros, Güntner, Francke, Mamede, and Carlos de Araújo (2010) in Brazil showed that the spatial pattern of sediment connectivity within catchment changes as a function of landscape and land use. The high variation in sediment deposit and sediment yield could also be attributed to the effects of SWC measures, topography, land use and geology on transport in a variety of other studies (Baartman, Masselink, Keesstra, & Temme, 2013; de Vente et al., 2008; Marchamalo et al., 2016; Stall, 1985; Verstraeten et al., 2002).

4. Conclusion and recommendations

Runoff and suspended sediment concentration (SSC) were monitored at the outlets of three main sub-watersheds of Koga catchment, North-Western Ethiopian highlands during 2016-2017. The WATEM/SEDEM model was calibrated to quantify the effect of SWC measures on soil erosion and sediment yield. WATEM/SEDEM generally underestimated the effect of SWC measures in controlling soil erosion and sediment yield in all sub-watersheds. Soil erosion and sediment yield values were highly variable across study sub-watersheds. This is most likely due to the effect of SWC measures as well as biophysical characteristics such as topography, land use and soil types. The integrated use of bund structures, contour cultivation, strip cropping and grass strips had the highest impact on controlling soil erosion and sediment yield. Integration of bunds with one or more agronomic and vegetative measures shows a higher effect on soil erosion and sediment yield in the study sub-watersheds. This emphasises that the use of bund structures alone is not sufficient as conservation strategy to control runoff and soil erosion in NW Ethiopian highlands. This study demonstrates that the harmful effects of soil erosion remain significant in Koga catchment and the Koga reservoir at the outlet of Koga river is highly affected by sedimentation. The calibration of WATEM/SEDEM at sub-watershed level has provided good model performance for simulated erosion and sediment yields. Therefore, WATEM/SEDEM adequately represents the underlying erosion and sedimentary processes and can be further used to evaluate the impacts of land use change and existing or new SWC scenarios. The model output results emphasises the importance of integrated use of conservation strategies to reduce soil erosion and sediment delivery. Using a spatially explicit modelling approach, as done in this study, increases insight in the spatially explicit effect of various measures on erosion rates, as opposed to measurement of sediment yield at the outlet of a catchment.

Data available statement

The datasets generated during and/or analysed during the study are available from the corresponding author on reasonable request.

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***Table 1** Crop management (C) factor and the physical conservation (P)factor for Ethiopian highlands*

Land use	C factor	SWC measure	P factor
Cultivated	0.19	Bunds	0.42

Land use	C factor	SWC measure	P factor
Degraded pasture	0.05	Grass strips	0.70
Dense grass	0.01	Contour cultivation	0.91
Forest	0.008	Strip cropping	0.84
Bushland	0.04	Fallow ploughed	0.65
miscellaneous land	0.05	No conservation	1.00

***Table 2** SWC scenarios simulated for Asanat, Debre Yakob and Rim sub-watersheds.*

Scenario	Physical measure	Agronomic practices	Vegetative measure
Scenario I	Bunds	-	-
Scenario II	Bunds	CC	-
Scenario III	Bunds	CC + SC	-
Scenario IV	Bunds	CC + SC	GS
Scenario V	No	-	-

NO: no SWC, CC: contour cultivation, SC: strip cropping, GS: grass strips

Table 3 Observed and predicted sediment yield (t ha^{-1} y^{-1}) for the study sub-watersheds

SY: sediment yield, NSE: Nash-Sutcliff efficiency

Sub-watershed	Observed SY	Predicted SY	NSE
Asanat	35.6	36.1	0.83
Debre Yakob	24.4	25.1	0.56
Rim	31.7	32.5	0.72

SY: sediment yield, NSE: Nash-Sutcliff efficiency

***Table 4** The results of total erosion, sediment deposition and yield (t ha^{-1} y^{-1}) estimated by WATEM/SEDEM for the study sub-watersheds.*

Asanat	Asanat	Asanat	Asanat	Asanat
Scenario	SWC measures	Erosion	Deposition	Sediment yield
I	B	51.7	15.6	36.1
II	B+CC	47.9	14.5	33.4
III	B+CC+SC	45.6	13.8	31.8
IV	B+CC+SC+GS	35.6	18.6	17.0
V	NO	81.2	14.3	66.9
Debre Yakob	Debre Yakob	Debre Yakob	Debre Yakob	Debre Yakob
Scenario	SWC measures	Erosion	Deposition	Sediment yield
I	B	40.5	15.4	25.1
II	B+CC	36.8	13.3	23.5
III	B+CC+SC	32.9	10.7	22.2
IV	B+CC+SC+GS	25.3	11.4	13.9
V	NO	66.8	25.7	41.1
Rim	Rim	Rim	Rim	Rim
Scenario	SWC measures	Erosion	Deposition	Sediment yield

Asanat	Asanat	Asanat	Asanat	Asanat
I	B	44.9	12.4	32.5
II	B+C	39.0	11.7	27.3
III	B+CC+SC	34.3	12.6	21.7
IV	B+CC+SC+GS	24.5	12.0	12.5
V	NO	68.7	9.7	59.0

NO: no SWC; B: bunds; CC: contour cultivation; SC: strip cropping; GS: grass strips

Table 5 Channel slope and length, and SDR for the study sub-watersheds

Sub-water shed	SL (km)	SS (%)	Gross erosion (t/ha)	SY	SDR (%)
Asanat	6.8	27	67.3	36.1	53
Debre Yakob	2.3	16	55.9	25.1	44
Rim	4.6	8	57.3	32.5	56

SL: stream length, SS: mean stream bed slope, SY: sediment yield (t ha^{-1} y^{-1}), SDR: sediment delivery ratio

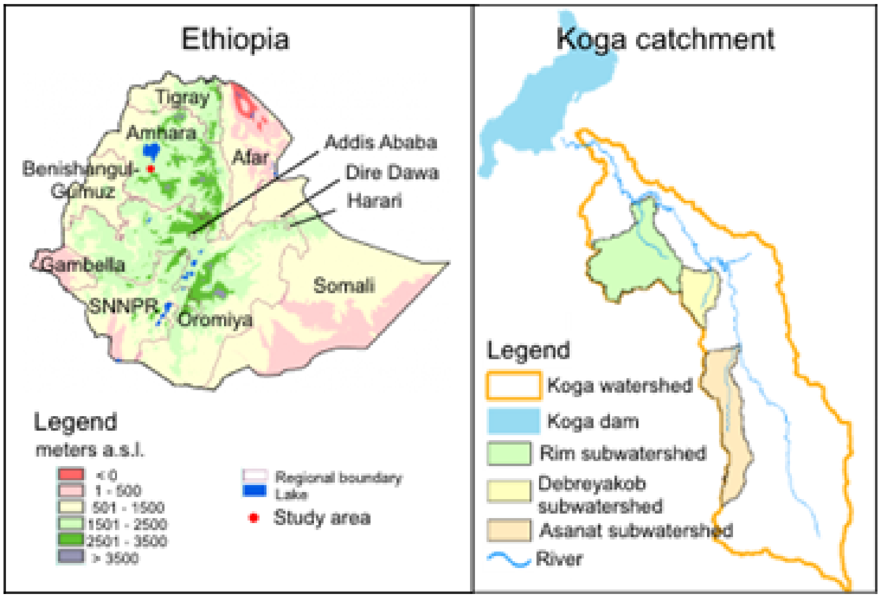
Figure1. *Location of Koga catchment in Ethiopia and study sub-watersheds within Koga catchment*

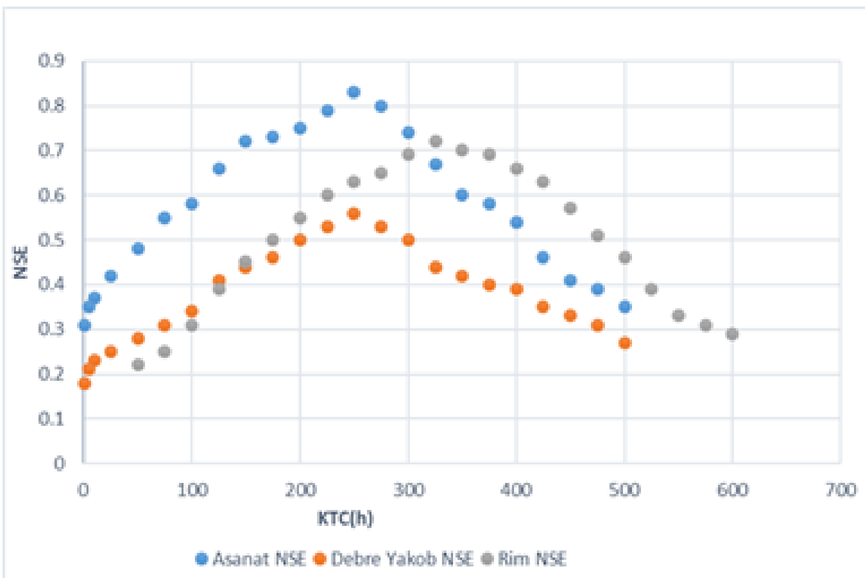
Figure 2. The KTC(h) calibration curves for Asanat, Debre Yakob and Rim sub-watersheds

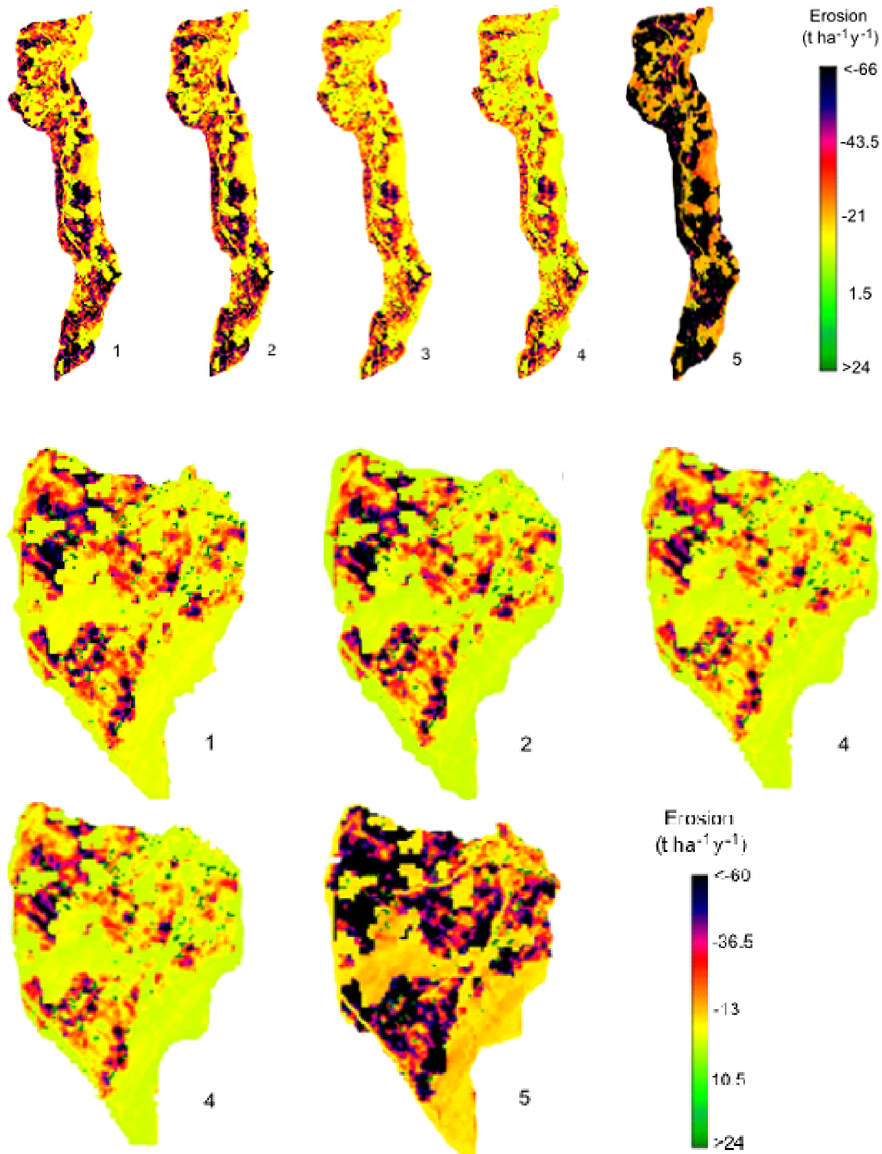
Figure 3. *Spatial pattern of soil erosion within the Asanat sub-watershed, according to the scenarios (I-V) simulated with the WATEM/SEDEM. Negative values represent net erosion whereas positive values present deposition.*

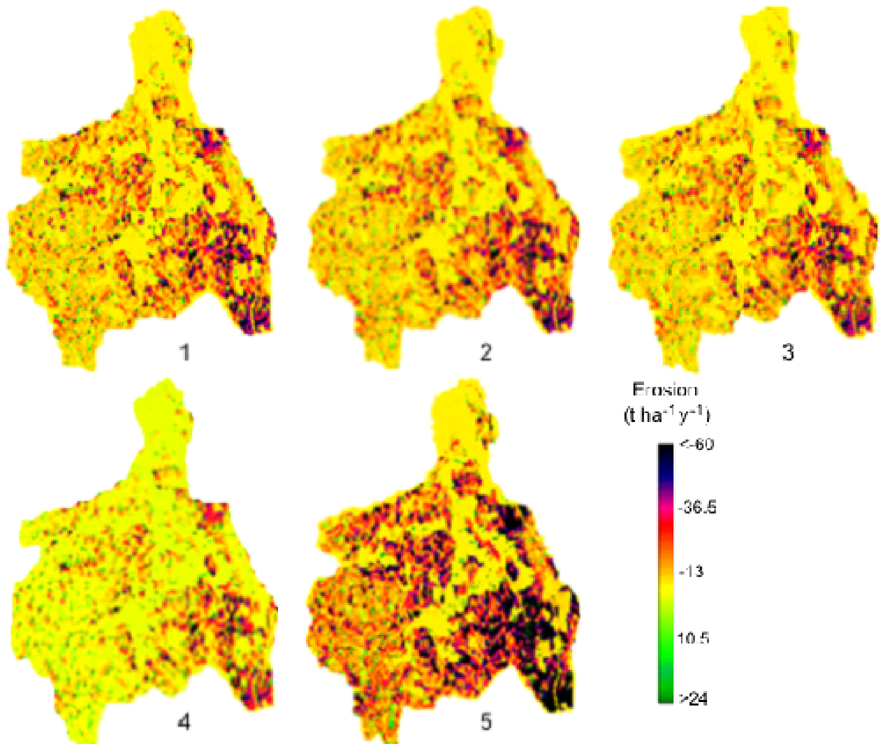
Figure 4 *Spatial pattern of soil erosion within the Debre Yakob sub-watershed, according to the scenarios (I-V) simulated with the WATEM/SEDEM. Negative values represent net erosion whereas positive values present deposition.*

Figure 5 *Spatial pattern of soil erosion within the Rim sub-watershed, according to the scenarios (I-V) simulated with the WATEM/SEDEM. Negative values represent net erosion whereas positive present deposition.*


Ethiopia
Tigray
Amhara
Afar
Benishangul-Gumuz
Addis Ababa
Dire Dawa
Harari
Gambella
Somali
SNNPR
Oromiya
Legend
meters a.s.l.
< 0
1 - 500
501 - 1500
1501 - 2500
2501 - 3500
> 3500
Regional boundary
Lake
Study area
Koga catchment
Legend
Koga watershed
Koga dam
Rim subwatershed
Debreyakob subwatershed
Asanat subwatershed
River


NSE
KTC(h)
Asanat NSE
Debre Yakob NSE
Rim NSE


Erosion
(t ha-1 y-1)
<-66
-43.5
-21
1.5
>24
1
2
3
4
5
1
2
4
4
5
Erosion
(t ha-1 y-1)
<-60
-36.5
-13
10.5
>24


1
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Erosion
(t ha-1 y-1)
<-60
-36.5
-13
10.5
>24