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Estimating landscape susceptibility to soil erosion using a GIS-based approach in Northern Ethiopia

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ABSTRACT

Soil erosion is a very critical form of land degradation resulting in the loss of soil nutrients and downstream sedimentation of water storages in the highlands of Ethiopia. As it is technically and financially impossible to conserve all landscapes affected by erosion, identification of priority areas of intervention is necessary. Spatially distributed erosion models can help map landscape susceptibility to erosion and identify high erosion risk areas. Integration of erosion models with geographic information systems (GIS) enables assessing evaluate the spatial variability of soil erosion and plan implementing conservation measures at landscape levels. In this study, the Revised Universal Soil Loss Equation adjusted for sediment delivery ratio was used in a GIS system to assess landscape sensitivity to erosion and identify hotspots. The approach was applied in three catchments with size being 10–20 km^2 and results were compared against quantitative and semi-quantitative data. The model estimated mean soil loss rates of about 45 t ha^{-1} y^{-1} with an average variability of 30% between catchments. The estimated soil loss rate is above the tolerable limit of 10 t ha^{-1} y^{-1}. The model predicted high soil loss rates at steep slopes and shoulder positions as well as along gullies. The results of the study demonstrate that knowledge of spatial patterns of high soil loss risk areas can help deploy site-specific conservation measures.

1. Introduction

Soil erosion is a fundamental problem in Ethiopia with tremendous impact on soil quality, land productivity, water pollution and sedimentation (e.g.,Tamene, Park, Dikau, & Vlek, 2006a; Hurni, 1983). In many areas of the mountainous regions of northern Ethiopia, erosion has caused critical loss of topsoil and rapid siltation of water harvesting reservoirs (Adimassu, Mekonnen, Yirga, & Kessler, 2014; Tamene et al., 2006a; Tilahun, Esser, Vägen, & Haile, 2002). To tackle the on- and off-sites damages due to erosion,adequate information on the rates and determinants of soil loss as well as spatial distribution of major sediment sources are needed. Since there are wide differences in the rates of sediment yield from different landscape units and application of conservation measures to all areas experiencing erosion is uneconomical and undesirable, conservation measures should be targeted to critical areas experiencing high soil loss. Identification of "hotspot" areas of erosion is therefore imperative from economic, management and sustainability point of view.

Soil erosion models are commonly used to investigate the physical processes and mechanisms governing erosion rates and identifying high risk areas of soil loss to aid conservation planning (Jetten, Govers, & Hessel, 2003; Mitasova, Batron, Ullah, Hofierka, & Harmon, 2013). Recent advances in the development of Geographic Information System (GIS) have promoted the application of distributed soil erosion and sediment delivery models at catchment scales (Kamaludin et al., 2013; Mitasova et al., 2013; Tanyas, Kolatb, & Süzenc, 2015).

Studies show that terrain shape and topographic complexity play dominant role on the spatial variation of hydrological processes at the catchment scale (Desmet & Govers, 1996a; Mitasova, Hofierka, Zloch, & Iverson, 1996; Van Oost et. al., 2000). Model formulation with topography being treated in more detail may thus allow reproduction of the basic patterns of erosion and deposition in complex landscapes (Wilson & Gallant, 2000). Soil erosion models that emphasize terrain can be the best compromise between the availability of input data and the reliability of soil loss estimates (Ferro, Di Stefano, & Minacapilli, 2003). The slope steepness-length component of the Universal Soil Loss

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Equation can be adjusted to appropriately simulate the impacts of complex terrain and various soil-and land-cover changes on the spatial distribution of soil erosion (Desmet & Govers, 1996; Mitasova et al., 1996; Moore & Burch, 1986; Moore, Turner, Wilson, Jensen, & Band, 1993; Wilson & Gallant, 2000). In this study the RUSLE adjusted for complex terrain (RUSLE3D)(e.g.,Desmet & Govers, 1996a; Mitasova et al., 1996) was applied to assess landscape sensitivity to erosion using a spatially distributed model in a GIS environment in northern Ethiopia. The RUSLE3D was integrated with sediment delivery ratio (SDR) to estimate sediment yield of catchments. The model was applied in three catchments of scale ca. 10–20 km^2 where different forms of erosion processes and a mosaic of heterogeneous environmental factors are observed. Model results were compared with sediment deposition in reservoirs and with data acquired from field surveys.

2. Materials and methods

2.1. Study area

The study was conducted in three catchments (Adikenafiz, Gerebmihiz and Laelaywukro) in the Tigray region of northern Ethiopia (Fig. 1). The sites were selected considering differences in basin characteristics such as terrain, lithology, land use/cover, erosion intensity and sediment deposition rates.

The Adikenafiz catchment has an area of 14 km^2 with an average slope of 11 degrees. Its landscape is dominantly covered with shale lithology with most of the upper position covered with sandstone. The majority of the lower and upper positions of the catchment (ca. 60%) are cultivated while the middle position is dominated with protected areas, grazing lands, bushes and shrubs lands. The topography of the landscape is convex which increases and accelerates runoff. Gullies are widespread and form spectacular features mainly in the lower positions.

Gerebmihiz catchment covers an area of about 20 km^2 with an average slope of 8 degrees. Its shape is not as convex and undulating as Adikenafiz but is very much similar in terms of lithology. The majority of the area is cultivated but also significant part is used for livestock grazing. Restricted grazing areas with dense grass cover are found at the lower position of the catchment. Gullies are as prominent as in the Adikenafiz catchment and the restricted grazing areas are split by wide and deep gullies.

Laelaywkro catchment has an area of 10 km^2 with an average terrain slope of 16 degrees. This catchment has the most complex terrain among the three and is also dominantly covered by sandstone. Unlike the other two catchments, the most top part of this catchment is flat and majority is cultivated. The middle position has very complex and steep terrain with high potential runoff. Gullies are not as widespread as in the two sites and the middle position of the catchment is well treated with conservation measures.

2.2. Estimation of soil erosion factors

Soil erosion is a function of terrain, rainfall, soils, land cover and land use as well as management practices (Renard & Foster, 1983). Spatially distributed data on these factors are necessary to assess the rates and patterns of soil loss and identify areas that require priority management intervention. Since the northern part of

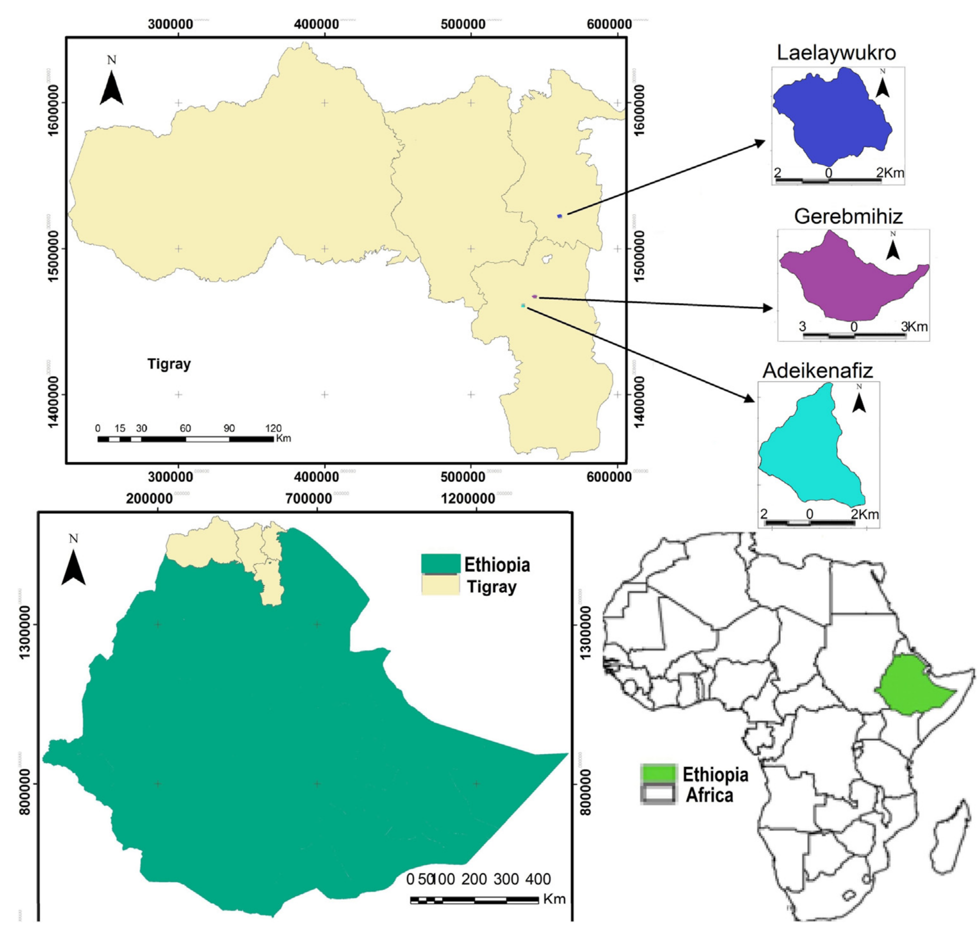

Fig. 1. Location of study sites in Tigray, northern Ethiopia identified to estimate soil loss pattern.

Ethiopia is characterized by very complex terrain configuration, the RUSLE model adjusted to handle complex terrain (RUSLE3D) was used in this study. The RUSLE3Dis based on all the other RUSLE erosion factors except that the slope-length factor is emphasized to represent complex terrain adequately (Desmet & Govers, 1996a; Mitasova et al., 1996) and is given as:

$$\text{RUSLE3D}\left(\text{t ha}^{-1}\text{y}^{-1}\right)=\text{RKLSCP} \tag{1}$$

where R = rainfall erosivity (MJ mm ha^{-1} h^{-1} y^{-1}); K = soil erodibility (t ha h (ha MJ mm)$^{-1}$); LS =3D terrain representation (-); C = land use/cover (-); and P= conservation/management (-) factor. Key steps employed to derive the six erosion factor components are described below.

2.3. Terrain representation (slope length factor) in the RUSLE3D model

To capture the impact of terrain on soil redistribution, detailed digital elevation model (DEM) is required for the study sites under consideration. DEMs were constructed for each catchment in ArcGIS 10.2.2 after digitizing contours, streams, and spot heights from contour maps of scale 1:50000 (Ethiopian Mapping Authority, 1997). Considering the contour spacing of catchments (20 m) and in order to obtain a reasonably detailed representation of terrain parameters and their derivations, the DEMs were produced at 10 m gird cell size. After DEMs were created, pits/sinks were filled before any processing was undertaken in order to “route” runoff to the catchment outlet without facing “unnecessary obstacles”. Once DEMs were created and cleaned, the following equation was used to calculate the ‘slope-length’ (LS) component of the RUSLE3D model (Mitasova et al., 1996; Moore et al., 1993).

$$LS=(m+1)\left[\frac{A_s}{22.13}\right]^m\left[\frac{\sin\beta}{0.0896}\right]^n \tag{2}$$

where A_s= specific upslope contributing area per unit length of contour; β = local slope gradient (degrees); m and n = empirical constants for slope length and angle.

At a catchment scale, the upslope contributing areas (A_s) is preferred over the slope-length (*LS*) approach, since upstream area rather than slope-length is the key determinant factor of runoff above every point (Desmet & Govers, 1996a; Gallant & Wilson, 2000; Mitasova et al., 1996). The A_s substitution for the *LS*- factor could therefore better represent complicated flow divergence and convergence patterns that are inevitable within the high mountainous complex terrain of the study area (Mitasova et al., 2013). The A_s can be calculated based on (Desmet & Govers, 1996b; Gallant & Wilson, 2000; Mitasova et al., 1996; Park, McSweeney, & Lowery, 2001):

$$A_s=\frac{1}{b_i}\sum_i^N a_i\mu_i \tag{3}$$

where a_i= the area of i_{th} grid cell; b = the contour width of the i_{th} cell (approximated by cell resolution); μ_i= the weight depending upon the runoff generating mechanism and infiltration rates; N = the number of grid cells draining into grid cell i.

In order to account for the role of both flow convergence and divergence on erosion/deposition processes, the multiple flow algorithm suggested by Freeman (1991) available in DiGem (Conrad, 1998) was used to calculate the A_s term in this study.

2.4. Rainfall erosivity (R) factor

The *R* factor, defined as the product of kinetic energy and the maximum 30 min intensity, shows the erosivity of rainfall events (Renard, Foster, Weesies, McCool, & Yoder, 1997; Wischmeier & Smith, 1978). Since rainfall intensity data is not available in most developing countries to calculate the R factor, different studies calibrated relationship between mean rainfall amount and rainfall erosivity for their respective conditions. For this study, the relationship between mean annual rainfall and rainfall erosivity established for Ethiopian condition based on the analysis of monthly rainfall data of different stations (Hurni, 1985) was used:

$$R=-8.12+0.562Pr \tag{4}$$

where R = annual rainfall erosivity (MJ mm ha^{-1} h^{-1} y^{-1}), and Pr = average annual precipitation (mm) of nearby stations acquired over the last 35 years.

Annual rainfall data acquired over the last 35 years from the nearest rainfall stations of each catchment were used in this study. Since the spatial variability of rainfall within catchments is not significant, only single rainfall data of the nearby station to each catchment (ca. within 2–5 km) was used Pr =599 mm for Adikenafiz and Gerebmihiz and P=673 mm for Laelaywukro).

2.5. Soil erodibility (K) factor

The *K* factor is defined as the rate of soil loss per unit of *R* on a unit plot and indicates the relative ease at which the soil is detached and transported (Renard et al., 1997). Soil erodibility is mainly a function of texture, organic matter (OM) content, structure and permeability and can be determined based on (Renard et al., 1997; Wischmeier, Johnson, & Cross, 1971):

$$100K=[2.1M^{1.14}\left(10^{-4}\right)(12-OM)+3.25(s-2)+2.5(p-3)]/7.59 \tag{5}$$

where K = erodibility factor in t ha h (ha MJ mm)$^{-1}$; M = particle size parameter = (%silt + %sand)*100 - %clay); OM = organic matter (%); s = soil structure code (-); p = permeability class (-). The division by 7.59 gives values in *SI* units of t ha (ha MJ mm)$^{-1}$.

For this study, data on soil properties were derived using pit description and laboratory analysis. Soil pits were located on representative sites considering terrain, land cover and surface lithology. Texture and organic matter were determined using laboratory analysis, permeability and structure were acquired based on soil profile analysis. Interpolation method was used to produce K-factors maps based on erodibility values (Table 1).

2.6. Cover-management (C) factor

The *C* factor is defined as the ratio of soil loss from land with specific vegetation/crop cover to the corresponding soil loss from continuous bare fallow (Wischmeier & Smith, 1978; Kinnell, 2010). To account for the role of surface cover and drive C-factor values, land use/cover data were generated from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images of 15 m resolution. Because of the “patchiness” of parcels and the relatively similar reflectance between grazing areas and cultivated fields during the dry season, different enhancement and transformation such as Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI) and Principal Component Analysis (PCA) techniques were used to aid the separability of cover types. The maximum likelihood supervised classification algorithm was then performed on bands 1, 2, 3, and PCA-1 images to derive LUC types for the study areas. The accuracy of the classification was evaluated using an error matrix (Lillisand & Kiefer, 1994). The classification produced an overall accuracy value of 78–86%. The lower value for the Laelaywukro catchment was due to a shadowing effect of terrain, which influences the reflectance values of pixels. Once LUC maps were available, C-factor values adapted for Ethiopian conditions were extracted for each grid cell based on Hurni (1985) (Table 1).

Table 1
Soil erodibility (K), surface cover (C), and support practice (P) factors adapted for Ethiopian condition to estimate soil loss.

***Geomorphological unit** (Machado, Perez-Gonzalez, & Benito, 1996)*[a]	***K-factor***	***Land cover** (Hurni, 1985)*	***C-factor***	***Management type** (Hurni, 1985 **and** Eweg & Van Lammeren, 1996)*	***P-Factor***
Erosion remnants with soil cover	0.03	Dense forest	0.001	Ploughing up and down	1.0
Erosion remnants without soil cover	0.01	Dense grass	0.01	Strip cultivation	0.80
Badlands	0.04	Degraded grass	0.05	Stone cover (40%)	0.80
Scarps/denudational rock slopes	0.02	Bush/shrub	0.02	Protected areas	0.50
Alluvial fans	0.04	Sorghum, maize	0.10	Ploughing on contour	0.90
Alluvial plain and terraces	0.03	Cereals, pulses	0.15	Terraces	0.60
Infilled valleys	0.03	Ethiopian Teff	0.25		

Note: Ethiopian **Teff** - *Eragrostis tef.*

[a] This approach is used for the Adekenafiz catchment for which soil sample analysis and description was not done. For the Gerebmihiz and Laelaywukro catchments, Eq. (5) and the approach described are used to estimate K-factor.

2.7. Support practice (P) factor

The P factor gives the ratio between soil loss expected for a certain soil conservation practice to that with up-and down-slope ploughing (Wischmeier & Smith, 1978). Specific cultivation practices and conservation activities affect erosion by modifying the flow pattern and direction of runoff and by reducing the amount of runoff (Renard & Foster, 1983). In areas where there is terracing, runoff speed could be reduced with increased infiltration, ultimately resulting in lower soil loss and sediment delivery. For this study, P factor values were assigned considering local management practices and based on values suggested by Hurni (1985) and Eweg and Van Lammeren (1996) (Table 1). Data related to management practices were collected based on field visits and participatory mapping.

2.8. Estimating sediment delivery efficiency potential of catchments

There is a general understanding that all soils eroded from upslope may not be delivered to streams or outlets as the majority will rather be redistributed within the basin or catchment (Walling, 1983, 1990). The occurrence and magnitude of deposition are functions of location of sediment sources, material type and size, energy of flow, gradient over which the material moves, the roughness of the surface along the flow path and the distance from the `source to destination´(De Vente, Poesen, Arabkhedri, & Verstraeten, 2007; Dickinson, Rudra, & Wall, 1990; Walling, 1983). Sediment delivery ratio, the ratio of sediment delivered to a stream or an outlet to the total erosion from the contributing area, is commonly used indicator of sediment transport efficiency of watersheds (Dickinson & Collins, 1998; Walling, 1983).

In this study, basin catchment attributes were integrated in a GIS to estimate distributed sediment delivery efficiency of catchments. According to Ferro and Minacapilli (1995), the fraction of the gross soil loss from a given cell that actually reaches a continuous stream system is estimated as:

$$SDR = \exp(-\beta^* t_i) \tag{6}$$

$$t_i = \sum_{1}^{n} \frac{l_i}{v_i} \tag{7}$$

$$v_\mathrm{i} = \mathrm{R_i S_i^{1/2}} \tag{8}$$

where, $\beta =$ routing coefficient; $t_i =$ travel time (h) from a given cell; $l_i =$ channel length in the flow path (m) and usually equal to the length of the side or diagonal of a cell depending on flow direction in the cell; $v_\mathrm{i} =$ runoff velocity of a given cell (m/s); $\mathrm{R_i} =$ coefficients based on surface roughness characteristics (m/s); $S_i =$ slope gradient (m/m).

Experimental and simulation studies by Ferro et al. (2003) suggests different values of β depending on basin size, slope and the LS-factor used in determining soil erosion. For this study, we adopted a β value of -0.0051, which is suggested for catchments with relatively higher LS-factor (Ferro et al., 2003). Coefficients for surface roughness characteristics (R_i) are adapted from Haan, Barfield, and Hayes (1994) and Mutua, Klik, and Loiskandl (2006) for overland and shallow concentrated flow.

2.9. Data collection to evaluate model results

2.9.1. Reservoir sediment deposition data

Different studies have used sediment deposition in reservoirs to calibrate and validate spatially distributed soil erosion models (De Vente et al., 2007; Moore & Foster, 1990; Van Rompaey, Bazzoffi, Jones, & Montanarella, 2005). In this study, model results were compared with sediment deposition data available for reservoirs of the three catchments (Tamene et al., 2006a).

2.9.2. Soil profile data

Soil profile data such as presence and thickness of alluvial/colluvial deposits and degree of truncation of the top soil horizon can be used to assess the performance of erosion models (Desmet & Govers, 1995; Mitasova, Mitas, Brown, & Johnston, 1997; Turnage, Lee, Foss, Kim, & Larsen, 1997). For this study, soil profile data related to the truncation level of the A horizon, presence and corresponding thickness of buried soils and alluvial/colluvial deposits were used to assess whether the spatial patterns of soil loss predicted by the model correspond with the depth of soil profile and to semi-quantitatively verify the performance of the model. Information on A-horizon and buried soils was acquired from field assessment and pit description of representative sites within the Gerebmihiz and Laelaywukro catchments.

2.9.3. Catchment characterization based on erosion sensitivity scores

Since the soil profile data is based on selected locations, the result may not adequately represent the spatial dynamics of erosion within catchments. As a result, a transect-based characterization and ranking procedure was designed to assign catchments into different categories of sediment yield potential based on evidences of erosion and degree of catchment connectivity (PSIAC, 1968). Such semi-qualitative approach can help differentiate the erosion susceptibility of sub-watersheds and identify priority areas of conservation (e.g., Tamene et al., 2011; Wu & Wang, 2007; de Vente et al., 2006; Lawrence, Cascio, Goldsmith, & Abbott, 2004; Verstraeten, Van Oost, Van Rompaey, Poesen, & Govers, 2002; Hadley, Lal, Onstand, Walling, & Yair, 1985; PSIAC, 1968). Since

Table 2
Terrain attributes and scores for catchment characterization in terms of sediment sources and delivery potential in Tigray, northern Ethiopia.

	Dominant hill slope attribute - on-site erosion	Possible score		
		3	2	1
1	Surface cover (condition, density)	Poor	Medium	Good
2	Level of degradation (evidences of erosion)	High	Medium	Low
3	Position in relation to streams/gullies[a]	Near	Medium	Far
4	Availability of material for detachment	High	Medium	Low
5	Average slope steepness	Steep	Medium	Gentle
6	Shape of sub-catchment	Convex	Linear	Concave
7	Presence and extent of depositional sites	Low	Medium	High
8	Presence and status of conservation practices	None	Medium	High
9	Presence and intensity of other “disturbances”[b]	High	Slight	None
10	Average distance to reservoir	Near	Medium	Far
Total				
	Dominant gully/stream attribute - off-site delivery			
1	Drainage network (density of gully/stream)	High	Medium	Low
2	Status of gullies/streams (instability, collapse)	Severe	Slight	None
3	Average slope of gully/stream path	Steep	Medium	Gentle
4	Evidences of deposition at gully/stream floor	Low	Medium	High
5	Degree of meandering of flow[c]	Low	Medium	High
6	Degree of disturbance by livestock/ cultivation[d]	High	Medium	Low
Total				

[a] Proximity to permanent stream channels/gullies as proxy to sediment delivery potential.
[b] Presence and, if so, role of “disturbances” such as roads, construction sites, etc.
[c] The more the stream meanders, the more it may deposit sediment at “ox-bow” positions.
[d] Role of cultivation up to the very edge of gullies and grazing on gully edges/floors as well as the significance of animal burrowing.

Table 3
Gross soil erosion (RUSLE3D*, t ha^{-1} y^{-1}), sediment delivery ratio (SDR), and sediment yield (SY, t ha^{-1} y^{-1}) estimated for major land use/cover types of three catchments in northern Ethiopia.

Land cover category	**Adikenafiz**			**Gerebmihiz**			**Laelaywukro**		
	RUSLE3D	**SDR**	**SY**	**RUSLE3D**	**SDR**	**SY**	**RUSLE3D**	**SDR**	**SY**
Dense cover	48	*0.57*	29	*77*	*0.35*	*40*	*34*	*0.45*	*19*
Non-restricted grazing	143	*0.67*	97	*112*	*0.58*	*69*	*42*	*0.68*	*31*
Restricted grazing	12	*0.41*	5	*72*	*0.4*	*27*	*32*	*0.42*	*13*
Cultivated	94	*0.79*	75	*80*	*0.52*	*41*	*38*	*0.57*	*25*
Other	94	*0.78*	73	*74*	*0.59*	*44*	*18*	*0.62*	*11*
Average	78	0.6	56	83	0.45	44	33	0.55	20

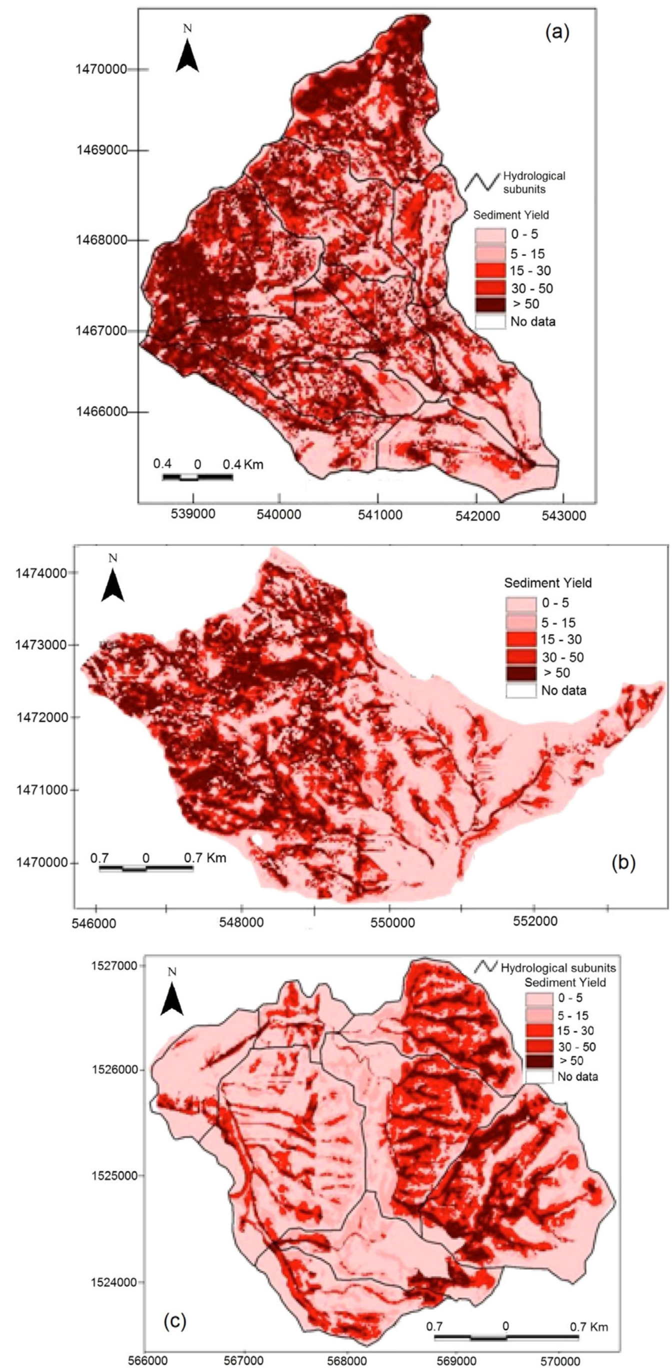

Fig. 2. Spatial patterns sediment yield for the studied catchments: (a) Adeikenafiz catchment, (b) Gerebmihiz catchment, and (c) Laelaywukro catchment.

watershed is a complex ecosystem with limited data available to understand its complexity, evidences show the importance of a knowledge-based approximate reasoning approach is for watershed assessment (Dai, Lorenzato, & Rocke, 2004). To achieve this, catchments were first sub-divided into subunits using standard procedure for delineating stream network and sub-basins from raster digital elevation models in ArcGIS. Individual factors that indicate susceptibility were then ranked for each subunit considering a series of erosion indicators to characterize landscape units in terms of their relative differences as active sources of sediment and sediment delivery efficiency to adjacent streams and reservoirs (Table 2). The factors shown in Table 2were associated with ordinal ranks of high, medium and low scores. These scores were assigned for each factor in each subunit and the summation of scores was assumed to reflect the relative differences in erosion risk and delivery potential of different subunits. Though we did not assign specific weights to each variable, we followed the analytical hierarchy process when ranking each sun-catchment in relation to the various factors (Banai, 1993; Schmoldt, 2013; Yalcin, 2008; Komac, 2006;Nekhay, Arriaza, & Boerboom, 2009). High score values means that anthropogenic and geomorphic attributes of subunits are such that they facilitate erosion and potential sediment delivery. The results were then compared with soil loss values predicted by the model for each subunit. Such approach is considered to be good alternative to assess the results of erosion models since field observation is relatively less error prone (Svorin, 2003; Vigiak, Okoba, Sterk, & Groenenberg, 2005).

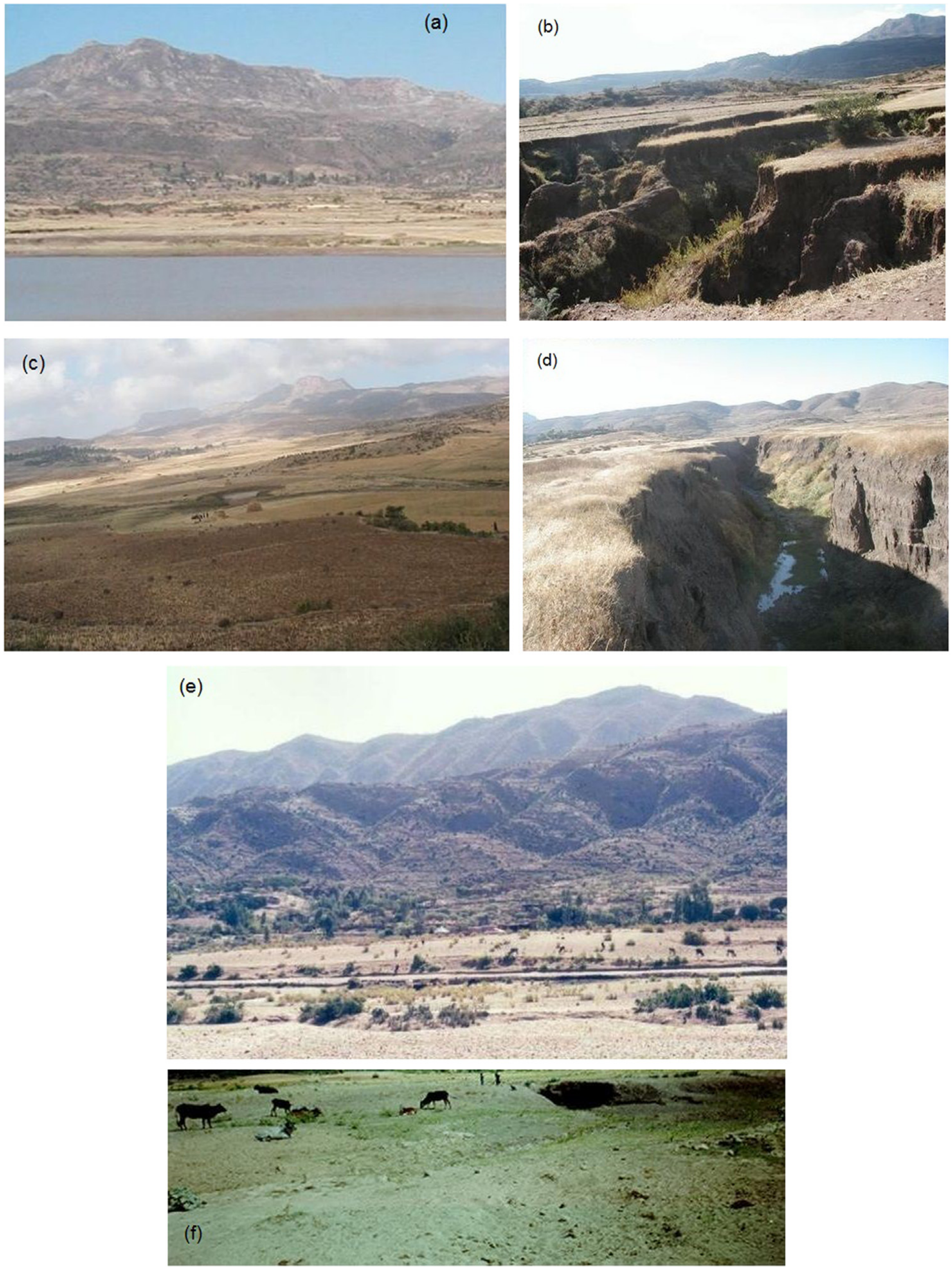

Fig. 3. Partial views of the studied catchments (a) Adikenafiz upslope, (b) Adikenafiz gullied cultivated land downslope; (c) Gerebmihiz upslope, (d) Gerebmihiz gullied grazing land downslope; (e) Laelaywukro pronounced terrain with relatively better surface cover and (f) Laelaywukro downslope and less erodible surface lithology.

3. Results and discussion

3.1. The rates and patterns of soil loss

The average annual net soil losses for the Adikenafiz, Gerebmihiz and Laelaywukro catchments as estimated by the RUSLE3D model are about 56, 44 and 20 t ha^{-1} y^{-1}, respectively. Close observation of the results show that about 30% of Adikenafiz and Gerebmihiz catchments experience soil loss rate of more than 25 t ha^{-1} y^{-1}. Those areas where catchment attributes that facilitate erosion such as poor surface cover, erodible lithology and collapsing network of gullies co-exist experienced high gross soil loss. The Adikenafiz and Gerebmihiz catchments which are dominantly covered with erodible lithology and poor surface cover show high soil loss rate though their terrains are not as complex as that of Laelaywukro. The Laelaywkro whose landscape is dominated by more erosion resistant sandstone and relatively good surface cover and land management show less erosion though the majority of its terrain potentially facilitates erosion.

In all cases the model predicted higher soil loss rate than the tolerable soil loss rate of 10 t ha^{-1} y^{-1} estimated for the country (Hurni, 1985). It is also important to note that the model predicted very high soil loss on few area of steep cliffs and gully/stream edges. When we exclude the extreme values around these areas which cover about 1.5% of the total area of each catchment, net soil loss reduces to 45, 38 and 12 t ha^{-1} yr^{-1} for the Adikenafiz, Geberbmihiz and Laelaywukro catchments, respectively.

Areas experiencing high gross erosion rates may not necessarily experience high sediment yield and thus may not be major sediment source areas. The averaged SDR of each catchment were 0.65, 0.46, and 0.54, for Adikenafiz, Gerebmihiz, and Lealy wukro catchments, respectively. The high sediment delivery ratio of the

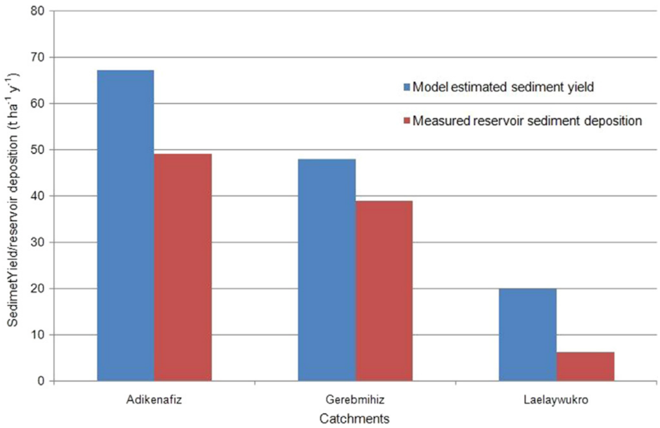

Fig. 4. Relationship between reservoir-based sediment yield estimates and model-based sediment yield predictions for two catchments in northern Ethiopia.

Table 4
Relation between soil profile data and RUSLE3D (adjusted for sediment delivery ratio) model results for Gerebmihiz and Laelaywukro catchments in Tigray, northern Ethiopia.

Site status	Number of pits observed		Proportion accurately predicted (RUSLE3D)	
	Gerebmihiz	Laelaywukro	Gerebmihiz	Laelaywukro
Stable[a]	7	–	4 (57%)	–
Eroding	15	6	10 (67%)	3(50%)
Aggrading	6	5	3 (50%)	5(100%)

Note: No soil profile data was available for the Adikenafiz catchment.

[a] Slope is gentle and there is no evidence of soil truncation or deposition, with soil loss and gain somewhat balanced (soil loss prediction is within ± 5 t ha^{-1} y^{-1}).

Adikenafiz catchment can be explained by its high height difference as well as its convex shape which enhances easy sediment delivery because transport capacity increases downslope (Medeiros, Güntner, Francke, Mamede, & De Araújo, 2010). Catchment connectivity is also high due to dense drainage network facilitating transport and delivery of eroded materials (Minella, Walling, Gustavo, & Merten, 2014; Walling & Zhang, 2004). The relatively low SDR for the Gerebmihiz catchment is due to its relatively flat terrain downslope and also because of the restricted grazing areas around the major gullies and near the reservoir. The relatively high SDR for the Laelaywukro catchment is partly because of its circular shape where sediment eroded upslope can be transported downslope relatively fast. Additionally, the majority of the landscape has steep slope gradient which reduces travel time of available sediment.

Generally, two locations that are equidistant from an outlet may not have the same travel time due to differences in slope, land use/cover type and catchment connectivity (Fernandez, Wu, McCool, & StÖckle, 2003). With regards to slope, SDR has a coefficient of variation of ca. 90% for areas with slope class 0 – 5 degrees. This is because of contrasting delivery efficiencies of flat areas with gullies and those where streams/gullies are not as prominent. This is especially the case in the Gerebmihiz catchment where gullies are widespread at relatively flat positions. For the Laelaywukro catchment, low SDR variability is observed at lower slope positions because there are no prominent gully features with high SDR compared to other areas. In terms of surface cover, SDR shows high variability on grazing lands which could be due to different levels of roughness across those areas. Especially in the Gerebmihiz catchment we can identify two distinct grazing areas, the common grazing and restricted grazing lands. SDR is lower for the restricted compared to the common grazing ones (Table 3). In addition, some of the common grazing lands have dense bushes/shrubs, which could retard flow and sediment movement compared to the barren areas that are generally over-grazed. In addition, travel time or distance of a given cell from streams or outlets also affects SDR, those closer to streams export most of the sediment delivered to and originated from them compared to those far from streams (Minella et al., 2014; Walling & Zhang, 2004).

Though net soil loss estimate for the Adikenafiz and Gerebmihiz catchments is generally high, the overall sediment yield estimates in this study are in general agreement with soil loss estimates made for different regions of the country. For instance, sediment yield estimates by Machado et al. (1996) for a catchment size of about 7 km^2 showed 21 t ha^{-1} y^{-1}. A reservoir survey study on small catchments in Tigray by Haregeweyn et al. (2005) estimated average sediment yield of ca. 5–20 t ha^{-1} y^{-1} while other studies show relatively higher sediment yield values (3–49 t ha^{-1} y^{-1}) for similar sites in the region (Tamene et al., 2006a). Studies in the 1980s report estimates of soil erosion rates in the Tigray region to be more than 80 t ha^{-1} y^{-1} (Tekeste & Paul, 1989). Other studies by Keyzer, Sonneveld, and Zoo (2001) showed that recorded measurements of soil loss in the highlands of Ethiopia could range from 3.2 to 84.5 t ha^{-1} y^{-1}. Long-term erosion plot studies by the SCRP project also showed that soil loss from cultivated lands in Ethiopia could amount to 40 t ha^{-1} y^{-1} (Hurni, 1990, 1993). The estimate made in this study also agrees well with another model-based sediment yield estimation made by Tamene and Vlek (2008) where application of the Unit Stream Power-based Erosion/Deposition model estimates average net soil loss of 14–50 t ha^{-1} y^{-1} for similar catchments in northern Ethiopia.

Fig. 2a, b, c show that the landscape positions where erosion is above the tolerable limit are located along main drainage lines and shoulder positions, as corroborated by observed gully and rill erosion. In addition to landscape position, tillage is another reason for the observed high soil loss rate along the shoulder positions (e.g., Govers, Quine, Desmet, Poesen, & Walling, 1996; Poesen et al., 1997) while the high soil loss due to gullies in less steep areas could be due to greater slop lengths (Kreznor, Olson, Banwart, & Johnson, 1989). Generally, pronounced terrain, poor surface cover, higher proportion of erodible lithology and dense network of gullies coincide in the Adikenafiz and Gerebmihiz catchments; (Fig. 3) increasing both soil detachment and transport processes (Poesen, Nachtergaele, Verstraeten, & Valentin, 2003; Tamene, Park, Dikau, & Vlek, 2006b). The Laelaywukro catchment shows relatively lower soil loss rate due to the fact that the majority of the catchments is characterized by resistant lithology (such as sandstone)and existence of conservation measures that can reduce runoff. Its flat downstream terrain can also encourage deposition due to fall in the kinetic energy of runoff. In the study sites, some steep slope areas also have good vegetation cover due to inaccessibility to human and livestock disturbances, resulting in lower net soil losses (Tamene et al., 2006b). Acquiring spatially distributed information on sediment yield and information on potential drivers allow implementing site-and context-specific management practices.

3.2. *Assessment of model results*

3.2.1. *Model result assessment using sediment deposition data*

Fig. 4 shows the relationship between sediment depositions to reservoirs estimated based on reservoir survey and net soil loss predicted by the RUSLE3D-SDR model. The figure shows that the sediment yield estimated by the model is in good agreement with

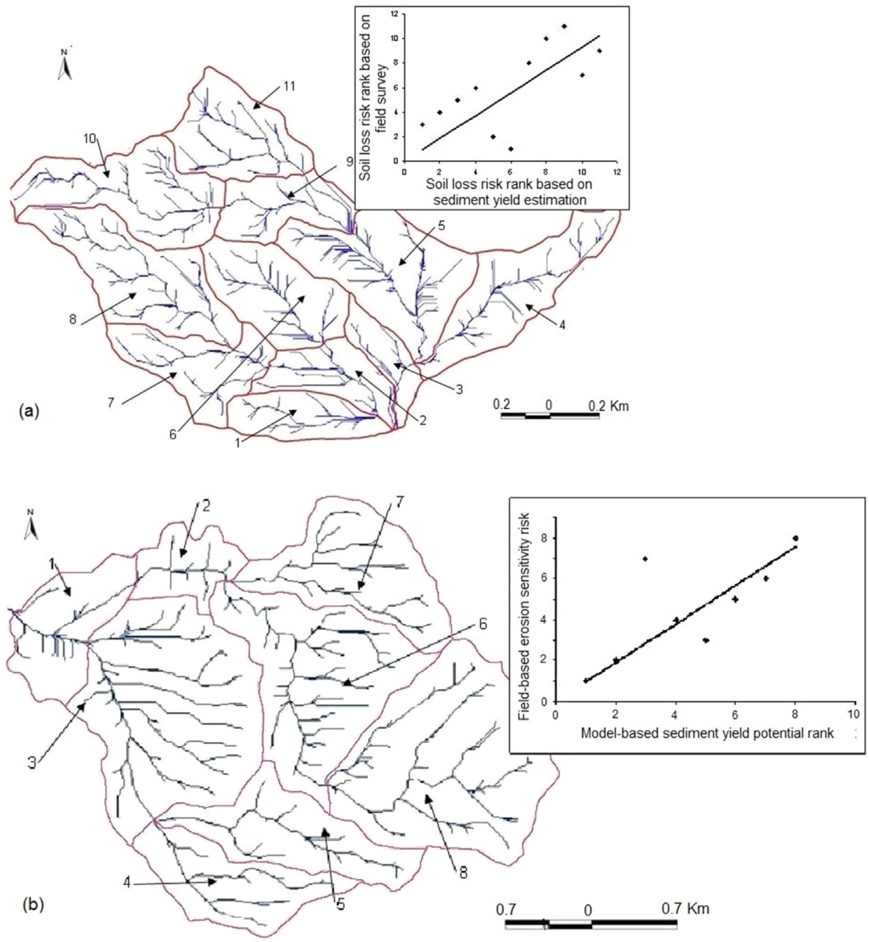

Fig. 5. Relationship between model-based sediment yield and field-based erosion risk assessment of (a) Gerebmihiz and (b) Laelaywukro catchments. Numbers represent different hydrological units. The axes vales for the graphs are ranked ordinal values of model- and field- based erosion assessment results.

what is accumulated in the reservoirs (Pearson's r > 0.97, $\alpha = 0.01$). The mean square error, which compares the observed (reservoir-based) and predicted (model-based) sediment yield estimates for the three sites was used to evaluate whether the model results fit the observed sediment deposition data. The result shows that the overall error of the model was ca. 5 t ha^{-1} y^{-1}, which is about 15% of the mean value of the observed sediment deposition. This can be considered acceptable considering the heterogeneous attributes of the catchments and the quality of data related to erosion factors. As a result, the model can be applied in the region to estimate net soil loss with an adequate level of accuracy provided that the different erosion factors are estimated at reasonable detail and accuracy.

3.2.2. Evaluation of spatial patterns of erosion using soil profile data

Table 4summarizes the relationship between soil profile depth and model-based sediment yield predictions for Gerebmihiz and Laelaywukro catchments. For the Gerebmihiz catchment, the model predicts high erosion in about 67% of truncated profile and predicted low soil loss in 50% of observed buried soil sites (Table 4). In most cases, at sites where truncated soil profile was observed, the model estimated high soil loss rate of more than 20 t ha^{-1} y^{-1} whereas at locations of buried soil or colluvial/alluvial deposit, the model predicted soil loss of less than 5 t ha^{-1} y^{-1}. In the Laelaywukro catchment, truncated soil profiles were observed for high soil loss areas (50%) and buried soil profiles were observed for low soil loss areas in 8 (100%) of the observed soil profile sites. The model very well predicted areas of high alluvial deposition at the lower position of the catchment. Most of the disagreements were located at the upslope positions where it predicted slight erosion for sites with truncated soil profiles. This may be because the soil truncation is due to repeated cultivation and not merely because of high soil loss due to erosion.

3.2.3. Evaluating spatial patterns of erosion using erosion sensitivity scores

Fig. 5 shows the relationship between model-based sediment yield potential rank and the field-based erosion sensitivity risk for Gerebmihiz and Laelaywukro catchments. The values in the figure are ordinal representations of the relative differences in soil erosion/sediment yield of each subunit. The figure shows that there is generally good agreement between the model- and field-based erosion risk assessment approaches. The agreements are relatively better for the Laelaywukro catchment compared to that of Gerebmihiz (Fig. 5). This is due to the fact that the model predicts relatively lower sediment yield on lower slope position but field evidences show high levels of gully erosion and gully bank collapse in the Gerebmihiz catchment(Fig. 5). For instance, subunit 1 in the Gerebmihiz catchment is mainly comprised of cultivated land with collapsing gullies indicating higher erosion risk. However, the model predicts relatively low sediment yield in those areas mainly due to flat terrain and restricted grazing areas. For the Laelaywukro catchment, differences are observed in areas of steep slopes where the model-based estimation shows high sediment yield (due to high *LS*-factor) but field-based erosion assessment shows lower erosion risk. This is because higher slope areas in the catchment experience relatively low sediment yield due mainly to resistant lithology.

Most of the good agreements are related to the low and high soil loss categories for the Laelaywukro and Gerebmihiz catchments. Knowledge of such areas helps to prioritize conservation management planning by excluding low soil loss zones and focusing on high soil loss areas.

4. Conclusion

This study demonstrates that spatially distributed models that do not require extensive data can be applied to provide a reasonable guide for identifying conservation priority areas. The Revised Universal Soil Loss Equation model adjusted for complex terrain applied in this study showed that the rate of soil erosion in most of the studied catchments is above the rate that can be tolerated. The model adequately identifies areas of high sediment yield which need to be prioritized for management intervention. Based on the rates and spatial patterns of soil loss, it can be generalized that reservoirs located at the confluence of collapsing gullies upslope will experience high siltation risk and thus need to be conserved before constructing dams. Such simplified information should be of great value to decision makers and planners in pinpointing locations where intervention is necessary to reduce soil loss from catchments and its delivery into reservoirs. However, it generally appears that the model over predicts soil loss on areas of complex topography, which means that its performance could vary for different sites highlighting that there is no single model that can be applicable to different sites with diversified attributes. It is thus necessary to calibrate and validate before applying models to evaluate their applicability to the environmental conditions of areas under consideration.

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