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ASSESSMENT OF SOIL EROSION HAZARD AND PRIORITIZATION FOR TREATMENT AT THE WATERSHED LEVEL: CASE STUDY IN THE CHEMOGA WATERSHED, BLUE NILE BASIN, ETHIOPIA

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ABSTRACT

Soil erosion by water is the most pressing environmental problem in Ethiopia, particularly in the Highlands where the topography is highly rugged, population pressure is high, steeplands are cultivated and rainfall is erosive. Soil conservation is critically required in these areas. The objective of this study was to assess soil erosion hazard in a typical highland watershed (the Chemoga watershed) and demonstrate that a simple erosion assessment model, the universal soil loss equation (USLE), integrated with satellite remote sensing and geographical information systems can provide useful tools for conservation decision-making. Monthly precipitation, soil map, a 30-m digital elevation model derived from topographic map, land-cover map produced from supervised classification of a Land Sat image, and land use types and slope steepness were used to determine the USLE factor values. The results show that a larger part of the watershed (>58 per cent of total) suffers from a severe or very severe erosion risk (>80 $t\,ha^{-1}\,y^{-1}$), mainly in the midstream and upstream parts where steeplands are cultivated or overgrazed. In about 25 per cent of the watershed, soil erosion was estimated to exceed 125 $t\,ha^{-1}\,y^{-1}$. Based on the predicted soil erosion rates, the watershed was divided into six priority categories for conservation intervention and 18 micro-watersheds were identified that may be used as planning units. Finally, the method used has yielded a fairly reliable estimation of soil loss rates and delineation of erosion-prone areas. Hence, a similar method can be used in other watersheds to prepare conservation master plans and enable efficient use of limited resources.

KEY WORDS: soil erosion; watershed treatment; USLE; Ethiopia; rusle

INTRODUCTION

Soil erosion constitutes a global environmental and economic problem (Pimentel *et al*., 1993, 1995; Lal, 2001). It causes loss of fertile topsoil and reduces the productive capacity of the land and thereby creates risk to global food security. It also affects negatively the natural water-storage capacity of catchments, design-life of man-made reservoirs and dams, quality of surface water resources, aesthetic landscape beauty and ecological balance in general. The fact that soil is almost a non-renewable natural resource over the human time-scale makes soil erosion a critical problem. Although many countries of the world suffer from the problem of accelerated soil erosion, the developing countries suffer more because of the inability of their farming populations to replace lost soils and nutrients (Erenstein, 1999).

In Ethiopia, one of the least developed countries of the world, soil erosion by water constitutes a severe threat to the national economy (Hurni, 1993; Sutcliffe, 1993; Sonneveld, 2002; MoARD and World Bank, 2007). According to Sonneveld (2002), the economic cost of soil erosion is around US$ 1·0 billion per year; while MoARD and World Bank (2007) state that the minimum annual cost of soil erosion ranges between 2 and 3 per cent of the national agricultural GDP. This clearly shows the extent to which soil erosion is a contributory factor to the country's structural food insecurity problem. The underlying cause for the excessive rate of soil loss is the unsustainable

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exploitation of the land resource which is manifested by extensive de-vegetation for fuelwood and other uses and expansion of cultivation and grazing into steepland areas (Tekele and Hedlund, 2000; Zeleke, 2000; Bewket, 2002; Amsalu *et al*., 2007). On the other hand, despite the considerable efforts made to develop and promote different types of soil and water conservation technologies, acceptance, adoption and sustained use by the land users have not been widespread for various reasons (Shiferaw and Holden, 1999; Bekele and Drake, 2003; Amsalu and de Graaff, 2007; Anley *et al*., 2007; Bewket, 2007). Soil erosion thus largely remains a problem to be tackled as part of the government's efforts at ensuring food security, poverty reduction and environmental sustainability.

Planning for and implementation of effective soil and water conservation measures in a site require, among other things, a detailed understanding of the extent, risk and spatial distribution of the problem; that is, soil erosion. It has immediate significance to conservation agencies, development agents and field technicians for a targeted and cost-effective conservation intervention by identifying most vulnerable landscapes and setting of priorities. The objective of this study was to assess soil erosion hazard in a typical highland watershed (the Chemoga watershed) in the Blue Nile basin and demonstrate that a simple erosion assessment model, the universal soil loss equation (USLE), integrated with satellite remote sensing and geographical information systems can provide useful information for conservation decision-making.

The USLE is an empirical equation that was developed to predict soil erosion rates from agricultural fields in the United States of America (Renard *et al*., 1994). It has, however, been used widely all over the world either in the original or modified form (Mellerowicz *et al*., 1994), including in Ethiopia (Hurni, 1985a,b; Helden, 1987; BCEOM, 1998), basically because of its simplicity and limited data requirement. Even though the equation was originally meant for predicting soil erosion at the field scale, its use in a GIS environment has enabled application for large areas and satisfactory results have been reported (Mellerowicz *et al*., 1994), for delineation of erosion-prone areas and prioritization of micro-watersheds for a targeted and cost-effective conservation planning purposes.

THE CASE STUDY SITE: THE CHEMOGA WATERSHED

The Chemoga watershed lies within 10°18′N to 10°39′N and 37°44′E to 37°53′E, and covers a total area of 346·9 km^2. It forms part of the Blue Nile basin in the northwestern highlands of Ethiopia, and it is characterized by diverse topographic conditions. The elevation ranges from 2420 to 3980 m (Figure 3). A mountainous and dissected terrain with steep slopes characterizes the upstream part; and an undulating topography and gentle slopes characterize the downstream part. The climatic condition is generally humid. The average annual total rainfall ranges from ~1216 mm in the downstream part to over 1470 mm in the upstream part of the watershed (Figure 1). As measured at Debre-Markos (10°20′N, 37°40′E and elevation 2411 m), the mean annual temperature is 14·5°C and it is much less than that in the upstream part owing to the high elevation, although measured data are unavailable. The temporal distribution of the rainfall is highly uneven and this gives rise to a serious shortage of water during the dry season in some parts of the watershed (Bewket and Sterk, 2005).

Subsistence agriculture is the source of livelihood to the population in the watershed. The farming system is a typical mixed crop–livestock system of the Ethiopian highlands. Land and livestock are therefore the most important assets to the people, with which they lead a sedentary life. Livestock provide the draught power and household members the labour that is needed for the farming operation. A variety of crops are produced by a household because of the strong orientation towards self-sufficiency. Barley (*Hordeum vulgare*), wheat (*Triticum vulgare*), oats (*Avena sativa*), horse beans (*Vicia faba*), potato (*Solanum tuberosum*) and onion (*Allium cepa*) are grown in the upstream part of the watershed; and *tef* (*Eragrostis tef*) is additionally cultivated in the downstream part. Crop production is the major source of income to the households. Incomes from off-farm employment, where the definition of off-farm employment included all activities outside of one's own farm: working on another farmer's farm, petty trading, weaving, carpentry, smithing and pottery are scanty (Bewket and Stroosnijder, 2004).

There are two fundamental reasons for selection of the Chemoga watershed as the site for this study. First, it is typical of the northwestern highlands of the country in terms of the various environmental attributes such as topography, soils, climate and the socioeconomic environment. Second, the watershed is part of the highlands that are known to be surplus producing regions, but presently threatened by resource degradation and impending food

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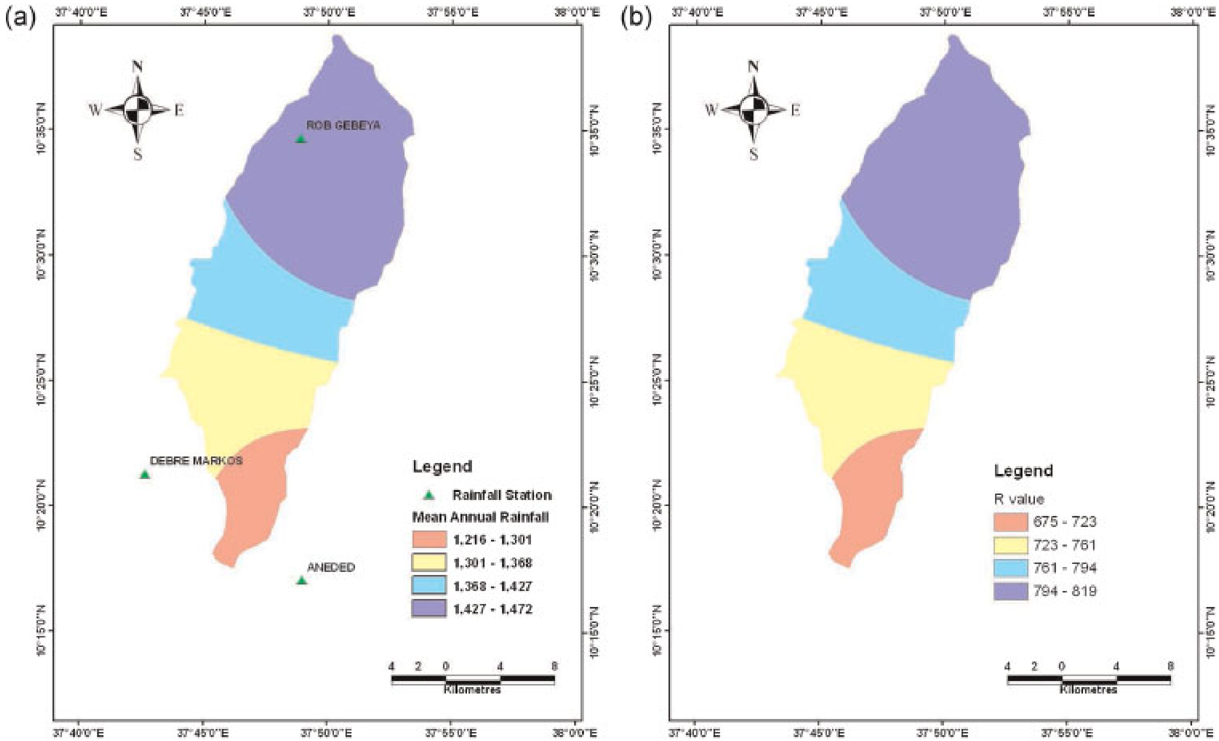

Figure 1. Mean annual rainfall (a) and rainfall erosivity (b) distribution in the Chemoga watershed. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

insecurity (Zeleke, 2000). Moreover, the Chemoga watershed is part of the Blue Nile basin, where soil erosion is a major problem with trans-boundary consequences. The trans-boundary environmental analysis for the Nile River basin undertaken under the auspices of the Nile Basin Initiative (NBI, 2001) has shown that the major environmental problem in the Ethiopian portion of the basin is watershed degradation due to soil erosion by water. Besides the on-site implications on local food security and sustainability of rural livelihoods, soil erosion has several off-site and downstream consequences. NBI (2001) stressed that watershed degradation from the Ethiopian highlands was a major contributor to the problems of flooding and reservoir siltation in the Sudan and Egypt. In other words, soil and water conservation and watershed management in this part of the basin will have positive downstream impacts, thus promoting cooperation among the Nile riparian states. Hurni *et al*. (2005) have shown empirically that watershed management in the Ethiopian highlands has potential benefits to downstream countries of the Sudan and Egypt in terms of both reduced sediment loads and regulated and more even water flows.

DETERMINING USLE FACTOR VALUES

The USLE estimates average soil loss for a given site as a product of six major factors (Equation 1), whose values can be expressed numerically. The equation was originally not intended to be used for a large area; however, satisfactory results were reported by various studies that used it on a large scale such as for watersheds (Mellerowicz *et al*., 1994; Mati *et al*., 2000). Also, it has often been used with some adjustments made in the estimation of the factors of erosion so as to obtain location-specific results. It was here used in a GIS environment to estimate average annual soil loss and the spatial distribution of erosion hazard in the watershed studied. The USLE is given as

$$A = RKLSCP \tag{1}$$

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where A is the annual soil loss ($\mathrm{t\,ha^{-1}\,y^{-1}}$), R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope length factor, S is the slope steepness factor, C is the crop management or land cover factor and P is the erosion control practice factor.

Rainfall Erosivity (R) Factor

Monthly rainfall records from three meteorological stations (Aneded, Debre-Markos and Rob-Gebeya) covering the period 1993–2007 were used to calculate the erosivity index. In the original equation of USLE, the value for R measures the kinetic energy of the rain and it requires measurements of rainfall intensity with autographic recorders; however, intensity data are not commonly available. Different empirical equations have been developed that estimate R values from rainfall totals, which is easily available. In the study area, there is no intensity data. Hence, an empirical equation developed by Hurni (1985a) that estimates R factor value from annual total rainfall was used. It is given as

$$R = -8 \cdot 12 + 0 \cdot 562P \tag{2}$$

where R is the rainfall erosivity factor, and P is the mean annual rainfall (mm). Similar methods of determining R factor values from rainfall totals have been used in previous studies from different countries (Morgan, 2005). Figure 1 shows the three rainfall stations, areal mean annual rainfall and distribution of rainfall erosivity in the study watershed.

Soil Erodibility (K) Factor

Soil map of the watershed was extracted from the master plan of the Blue Nile river basin (scale 1:250 000), which was obtained from the Ministry of Water Resources, and it was used to determine the K factor values. Soil erodibility depends on the physical and biochemical properties of soils and ranges from 0 to 1. Hence, determination of K factor values requires data on these parameters. To overcome unavailability of such data, Helden (1987) suggested K factor values for use in Ethiopia based on soil colour, which is believed to be a reflection of soil properties. Four different colours are recognized: black, brown, red and yellow, and their corresponding K factor values are 0·15, 0·2, 0·25 and 0·3, in order of sequence. A similar method of determining K factor values from colour of soils has also been suggested by the Soil Conservation Research Project (SCRP, 1996). Soil erodibility map of the watershed is shown in Figure 2.

Topographic (L and S) Factors

The L and S factors were generated from a digital topographic database that was created by digitizing three toposheets (1037-D1, 1037-D2 and 1037-B4), obtained from the Ethiopian Mapping Agency, covering the watershed at 1:50 000 scale and contour interval of 20 m, from which the watershed boundary and the drainage system were also derived. From the elevation information, slope and digital elevation model (DEM) with 30 m output cell size were prepared using grid-based GIS analysis. The resulting DEM was used to determine the slope length (L) and slope steepness (S) factors as follows:

$$L = \left(\frac{\lambda}{22 \cdot 13}\right)^m \tag{3}$$

$$S = (0 \cdot 065 + 0 \cdot 045x + 0 \cdot 0065x^2) \tag{4}$$

where λ is the projected horizontal distance in metres between the onset of runoff and the point where runoff enters a channel larger than a rill or deposition occurs, m is an exponent that depends on slope steepness, being 0·5 for slopes exceeding 5 per cent, 0·4 for slopes 3–5 per cent and 0·3 for slopes 1–3 per cent, and 0·2 for slopes $<1{\cdot}0$ per cent, and x is the slope in per cent.

In GIS-based application of USLE and its revised version RUSLE, the L and S factors are commonly quantified together as a product of the 2, as LS factor value (Moore and Burch, 1986; Moore and Wilson, 1992). Figure 3

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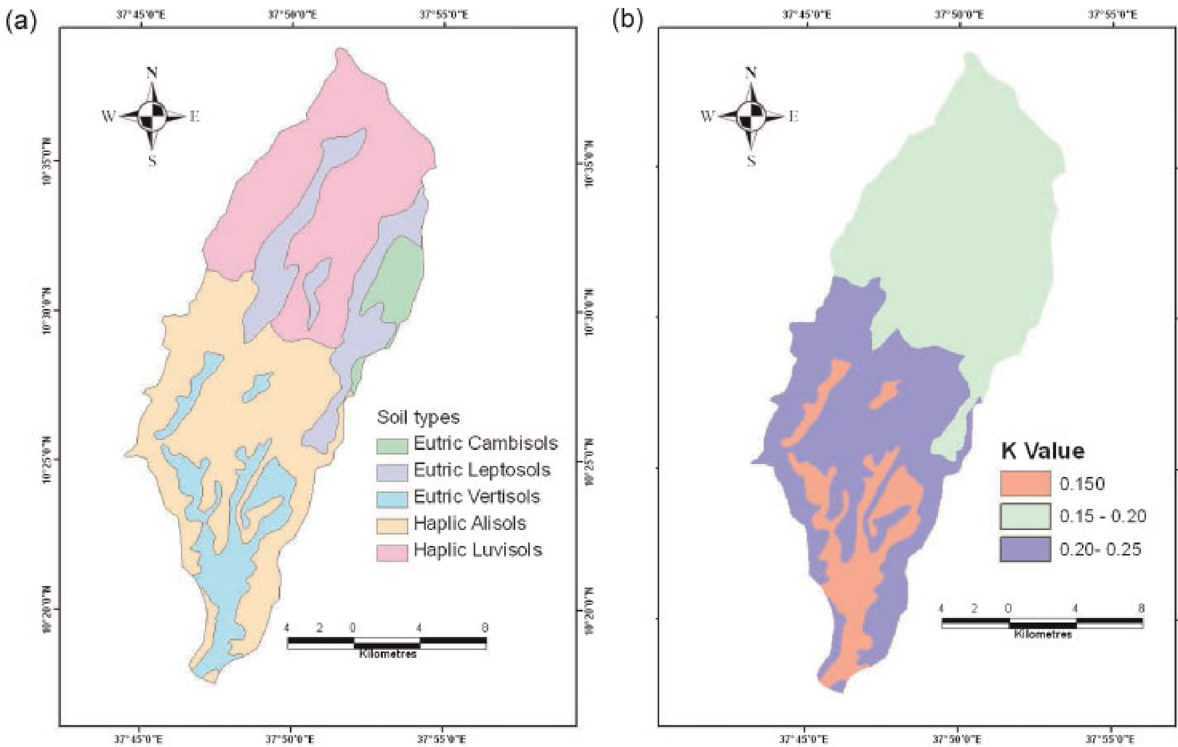

Figure 2. Major soil types (a) and soil erodibility (b) in the Chemoga watershed. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

shows the map of the topographic factors in the study watershed, which was determined as follows:

$$\mathrm{LS} = \left(\frac{\lambda}{22 \cdot 13}\right)^{m} (0 \cdot 065 + 0 \cdot 045x + 0 \cdot 0065x^{2}) \tag{5}$$

Cropping and Land-Cover (C) Factor

To determine the *C* factor values, a land-use and land-cover map of the watershed was prepared from a Landsat ETM+ imagery acquired on 8 March 2003 (path 169/row 053). Supervised digital image classification technique was employed, complemented with field surveys that provided on-the-ground information about the types of land-use and land-cover classes. Eight land-use and land-cover classes were recognized, and the corresponding *C* factor values were mapped (Figure 4). The identified land-use and land-cover classes were: afroalpine vegetation, forest, degraded forest, open woodland, grassland, cultivated, bareland and marshland. The *C* factor values for the different land-use and land-cover types as suggested in previous literature and used in the present study are shown in Table I. In the case of cultivated fields, the *C* factor values vary annually. The dominant crops in the watershed remain the same, however, and these are barely, oats and wheat, with some *tef* grown in the downstream part of the watershed. Hence, a value of 0·15 was used for all cropped areas.

Conservation Practices (P) Factor

The conservation practices factor values depend on the type of conservation measures implemented, and requires mapping of conserved areas for it to be quantified. In the study watershed, there is only a small area that has been treated with *fanya juu* bunds through the agricultural extension programme of the government, and these are poorly maintained as implementation was carried out in a top-down approach. The traditional conservation measure

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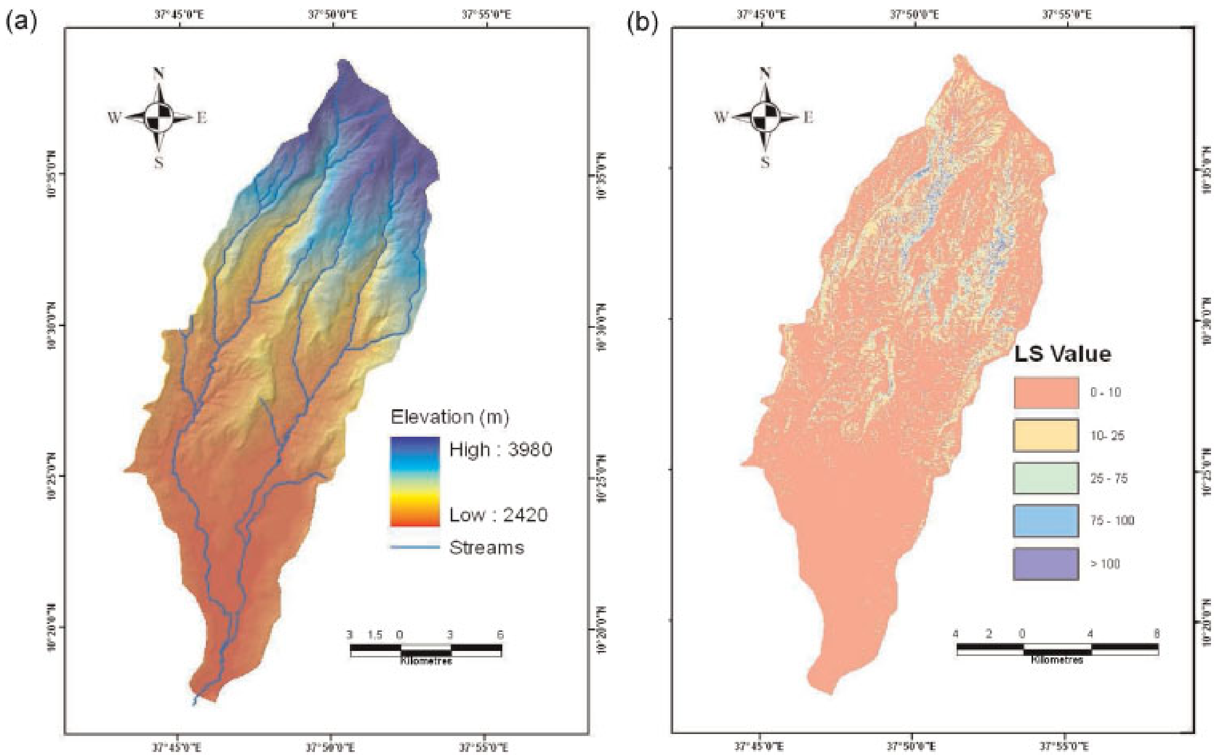

Figure 3. DEM (a) and topographic (LS) factors (b) in the Chemoga watershed. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

widely used is drainage ditch, locally known as **feses**, which is meant to safely drain excess runoff from croplands during rainstorms. The entire watershed area is therefore not treated with improved soil and water conservation measures. Hence, *P* factor values suggested by Wischmeier and Smith (1978) that considers only two types of land uses—agricultural and other—and land slopes were used in this study (Figure 5). As shown in Table II, the agricultural lands are classified into six slope categories and assigned *P* factor values, while all non-agricultural lands are assigned a *P* factor value of 1·00.

SOIL EROSION HAZARD

Soil erosion hazard was determined by multiplying the respective USLE factor values interactively in ArcGIS® using Equation (1), resulting in the erosion hazard map shown in Figure 6. Annual soil loss ranged from 0 in the downstream part of the watershed to over 80 t ha^{-1} y^{-1} in much of the midstream and upstream parts, and to well over 125 t ha^{-1} y^{-1} in some erosion hotspot areas (Figure 7). Average annual soil loss for the entire watershed was estimated at 93 t ha^{-1} y^{-1}. The estimated soil loss rate and the spatial patterns are generally realistic, compared to what can be observed in the field as well as results from previous studies. Based on field assessment of rill and inter-rill erosion, Bewket and Sterk (2003) estimated annual soil loss to range from 18 to 79 t ha^{-1} y^{-1} in parts of the same watershed. In 5 years of monitoring in a nearby experimental micro-watershed (the Anjeni) located ~40 km to the northwest, soil erosion from cultivated fields under the traditional land-use practices ranged from 17 to 176 t ha^{-1} y^{-1} (Herweg and Ludi, 1999). According to Herweg and Stillhardt (1999), soil erosion rates as high as 130–170 t ha^{-1} y^{-1} are not uncommon in cultivated fields in the Anjeni catchment, which has similar physical environmental and land-use conditions. FAO (1986) estimated average soil loss from croplands in the highlands as a

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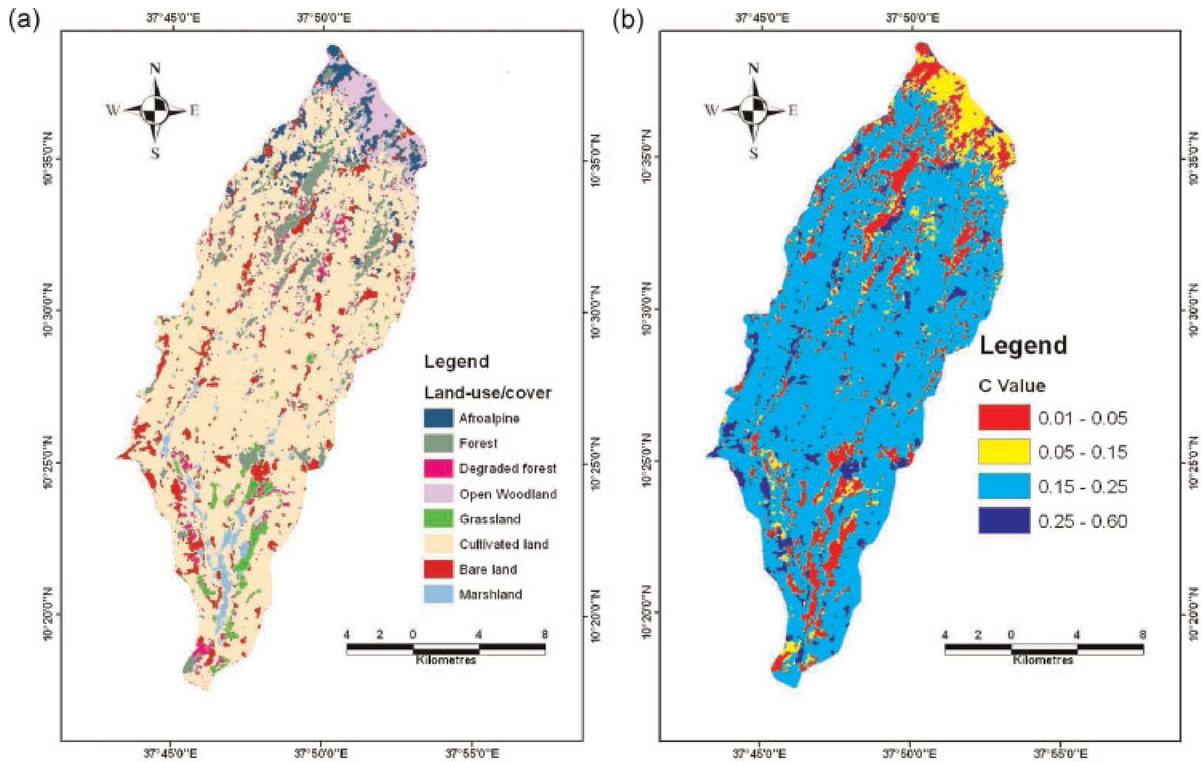

Figure 4. Land-use and land-cover types (a) and the cover factor (C) (b) values in the Chemoga watershed. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

whole at $100\,\mathrm{t\,ha^{-1}\,y^{-1}}$. Accounting for re-deposition of mobilized sediment, Hurni (1993) estimated mean soil loss from cultivated fields at $42\,\mathrm{t\,ha^{-1}\,y^{-1}}$.

Based on the estimated annual soil loss rates, the watershed was classified into six erosion severity classes (Table III). Accordingly, most of the area of the watershed (>58 per cent) was predicted to suffer from a severe or very severe erosion risk, which is in excess of $80\,\mathrm{t\,ha^{-1}\,y^{-1}}$. In about 25 per cent of the watershed, soil erosion was estimated to exceed $125\,\mathrm{t\,ha^{-1}\,y^{-1}}$. Severe or very severe erosion was found in the midstream and upstream parts of the watershed where steeplands are cultivated or overgrazed. In the midstream part of the watershed, it was observed in the field that the highest erosion damage was through gullies. The actual soil loss rates in this part of the watershed can therefore be much higher than estimated here by the USLE or those measurements from experimental plots of the SCRP, as both test plots and the USLE do not measure gully erosion. On the other hand, as

Table I. Cropping and land-cover (C) factor values used in different studies

Land-use and land-cover type	C factor value	References
Afro-alpine	0·01	BCEOM (1998)
Forest	0·01	Hurni (1985b)
Degraded forest	0·05	Hurni (1985b)
Open woodland	0·06	Eweg and van Lammeren (1996)
Grassland	0·01	Eweg and van Lammeren (1996)
Cultivated land (cereals/pulses)	0·15	Hurni (1985b)
Bare land	0·6	BCEOM (1998)
Marshland	0·01	BCEOM (1998)

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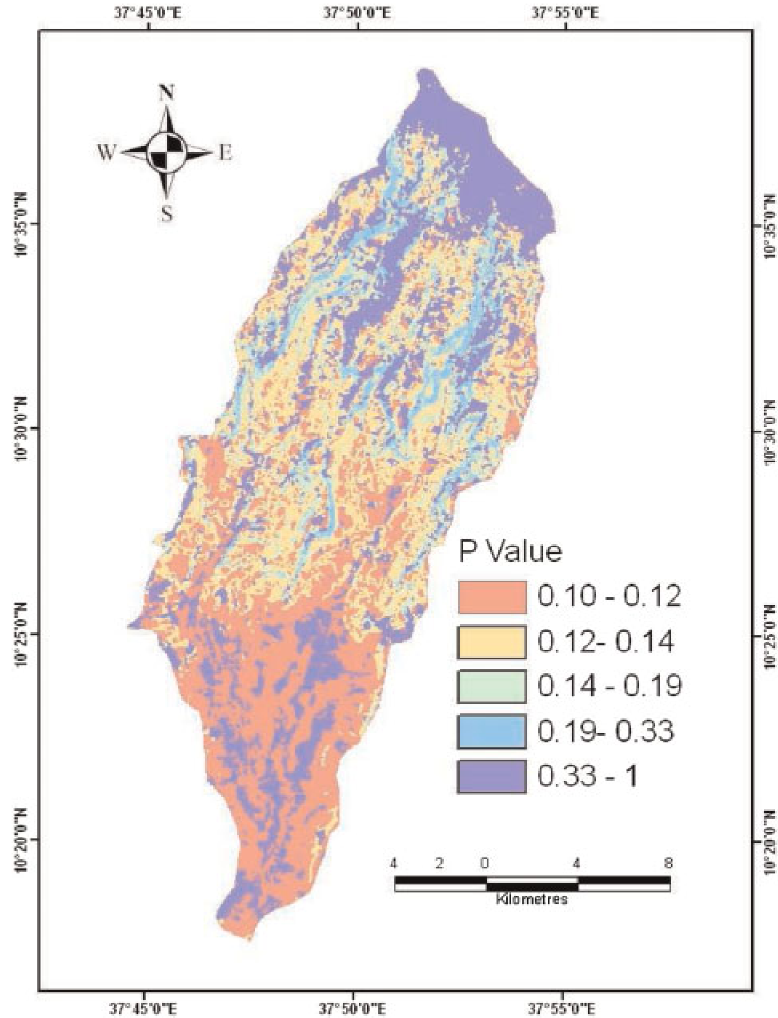

Figure 5. Conservation practices (*P*) factor values in the Chemoga watershed. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

Table II. The *P* factor values suggested by Wischmeier and Smith (1978)

Land-use type	Slope (per cent)	*P* factor
Agricultural land	0–5	0·1
	5–10	0·12
	10–20	0·14
	20–30	0·19
	30–50	0·25
	50–100	0·33
Other land	All	1·00

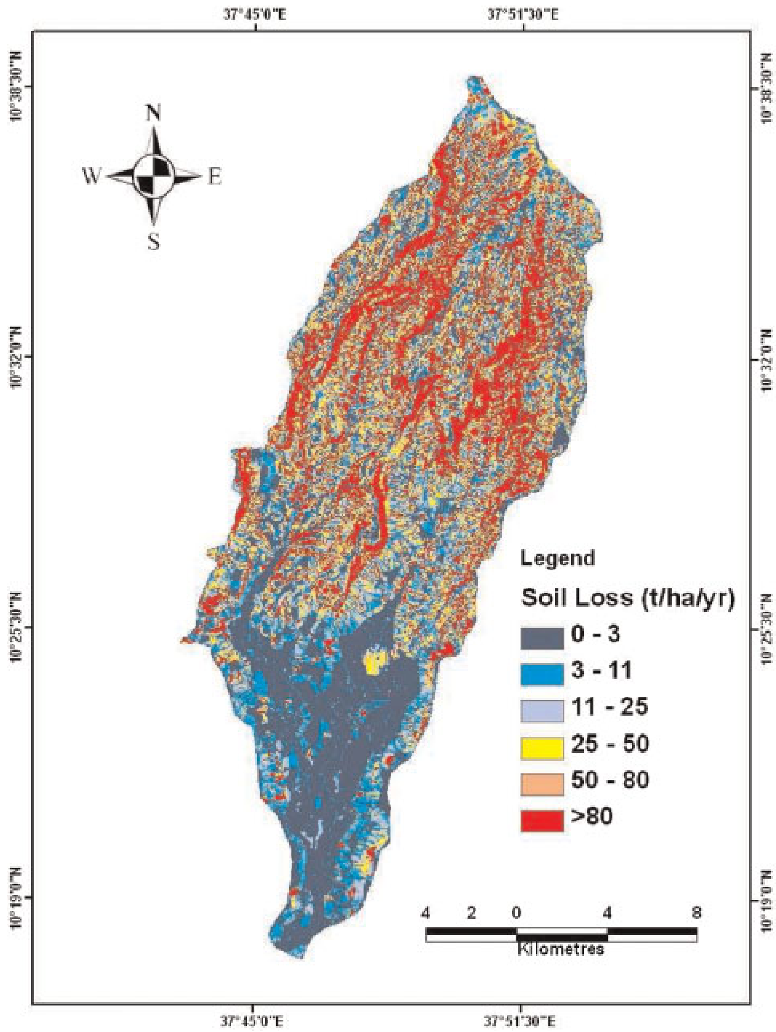

Figure 6. Soil erosion hazard in the Chemoga watershed. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

gullies are localized features, rill and inter-rill erosion still remain the dominant processes in most parts of the watershed making the USLE results useful.

In the downstream part (~25 per cent of total area), soil erosion was moderate or low. Indeed, a previous study has noted that a major erosion-related problem in this part of the watershed was deposition of eroded materials coming from the upstream part (Bewket, 2002). According to the same study, local people even constructed mud levees by their own initiative to contain the sediment within the stream channel, but without success. The relatively low soil loss value in the downstream part of the watershed was therefore mainly due to the low LS factor values (Figure 3). Erosion hazard was also relatively lower in the areas under natural vegetation cover, which is in agreement with plot level data that showed that annual soil loss rates in forested areas rarely exceeded 1 t ha^{-1} y^{-1} (Hurni, 1985b).

Prioritization for Watershed Treatment

The soil erosion hazard map (Figure 6) clearly shows that nearly the entire watershed requires implementation of different types of soil and water conservation measures for a sustainable land use. Resource considerations or

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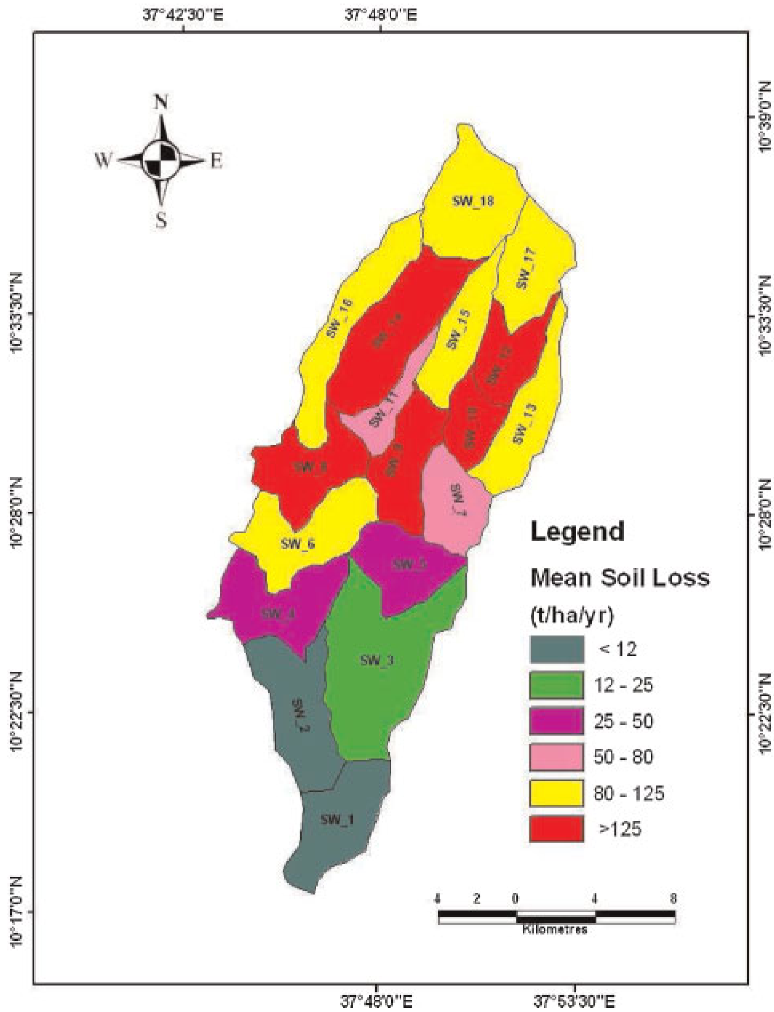

Figure 7. Soil erosion hotspots and micro-watersheds for conservation planning in the Chemoga watershed. This figure is available in colour online at www.interscience.wiley.com/journal/ldr

practicability of participatory watershed development may, however, limit implementation of soil and water conservation technologies to a few priority micro-watersheds only. Even where resource constraints are limited, implementing conservation measures in only selected micro-watersheds that are hotspots of erosion can significantly reduce total sediment yield of a watershed. Studies have shown that, for many watersheds, a few

Table III. Annual soil erosion rates and severity classes

Soil loss ($t\,ha^{-1}\,y^{-1}$)	Severity classes	Area (ha)	Per cent of total
<12	Low	4351·3	12·5
12–25	Moderate	4182·3	12·1
25–50	High	3731·3	10·8
50–80	Very high	2219·3	6·4
80–125	Severe	11 650·4	33·6
>125	Very severe	8552·2	24·7

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Table IV. Prioritization of micro-watersheds

Soil loss ($t\,ha^{-1}\,y^{-1}$)	Priority classes	Micro-watershed	Area (ha)	Per cent of total area	Per cent of total soil loss
>125	I	SW_8, SW_9, SW_10, SW_12, SW_14	8552·2	24·7	50·9
80–125	II	SW_6, SW_13, SW_15, SW_16, SW_17, SW_18	11 650·4	33·6	35·7
50–80	III	SW_7, SW_11	2219·3	6·4	4·6
25–50	IV	SW_4, SW_5	3731·3	10·8	4·7
12–25	V	SW_3	4182·3	12·1	3·0
<12	VI	SW_1, SW_2	4351·3	12·5	1·1

critical areas are responsible for a disproportionate amount of sediment yields (Mati *et al*., 2000; Tripathi *et al*., 2003). Thus, it is necessary and strategic to prioritize micro-watersheds for treatment with appropriate soil and water conservation measures. Prioritization of micro-watersheds involves ranking of the different micro-watersheds according to the order in which they ought to be taken up for treatment with conservation technologies by considering the amount of soil loss occurring.

In this study, a total of 18 micro-watersheds were delineated based on drainage systems and coded as SW_1 to SW_18 and the erosion hazard map was reclassified for the prioritization (Figure 7). Based on the spatial distribution of the erosion hazard, 11 out of 18 micro-watersheds fell under severe or very severe soil erosion categories of the soil loss severity classes (>80 $t\,ha^{-1}\,y^{-1}$), of which five and six were in the very severe and severe categories, respectively. These two groups of micro-watersheds were hence assigned the first and second priorities, in order of mention, for conservation planning (Table IV). The 11 micro-watersheds in the two erosion severity classes—severe and very severe—account for about 87 per cent of the total soil loss from the watershed, but cover only about 58 per cent of the total area of the watershed. Only five of the micro-watersheds in the very severe soil loss category account for about 51 per cent of the total soil loss from the watershed while accounting for only about 25 per cent of the total area of the watershed. This is in agreement with research results elsewhere that much of the total soil loss from a watershed comes from a small proportion of watershed areas (Mati *et al*., 2000; Tripathi *et al*., 2003). Of the 18 micro-watersheds, nine were predicted to experience annual soil loss of more than the watershed's average (93 $t\,ha^{-1}\,y^{-1}$), whereas in two other micro-watersheds (SW_6 and SW_18) estimated annual soil losses were close to the average (Table V).

Table V. Mean annual soil loss at micro-watershed level in the Chemoga watershed

Micro-watershed	Area (ha)	Per cent of total	Soil loss ($t\,ha^{-1}\,y^{-1}$)	Per cent of total
SW_1	2011·5	5·8	9·2	0·6
SW_2	2339·8	6·7	7·3	0·5
SW_3	4182·3	12·1	22·8	2·9
SW_4	2117·4	6·1	36·6	2·4
SW_5	1613·9	4·6	46·3	2·3
SW_6	2155·9	6·2	92·3	6·2
SW_7	1403·5	4·0	68·0	2·9
SW_8	1871·3	5·4	133·6	7·8
SW_9	1626·9	4·7	125·9	6·4
SW_10	970·6	2·8	228·5	6·9
SW_11	815·8	2·3	66·7	1·7
SW_12	1266·6	3·6	221·5	8·7
SW_13	1756·1	5·1	99·6	5·4
SW_14	2816·8	8·1	242·7	21·2
SW_15	1503·8	4·3	102·8	4·8
SW_16	2138·9	6·2	102·9	6·8
SW_17	1700·8	4·9	107·0	5·6
SW_18	2394·9	6·9	91·5	6·8

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The micro-watersheds SW_1, SW_2 and SW_3 that are predicted to experience low or moderate soil loss together cover about 25 per cent of the watershed area, but account for only 4·1 per cent of the total watershed soil loss. In prioritizing for conservation intervention, micro-watersheds SW_1 and SW_2 can be considered in the last (sixth) stage, and SW_3 can be considered in the fifth stage. The micro-watersheds SW_4 and SW_5, and SW_7 and SW_11 in the erosion severity classes of high and very high, respectively, were accorded conservation priorities of fourth and third in order of sequence.

DISCUSSION AND CONCLUSIONS

Soil erosion is a major contributor to the prevailing food insecurity in Ethiopia. Soil conservation is vital to the achievement of food security, poverty reduction and environmental sustainability in the country. The objective of this study was to assess soil erosion hazard in a typical highland watershed (the Chemoga watershed) in the Blue Nile basin and demonstrate that a simple erosion assessment model, the USLE, integrated with satellite remote sensing and geographical information systems can provide useful information for conservation decision-making. The important results of the study include soil erosion hazard map of the watershed and the prioritization of micro-watersheds into conservation priority categories, which can be used for preparation of a master plan for management of the watershed.

In selecting and implementing conservation measures for the different micro-watersheds, the concepts of soil loss tolerance and critical soil loss values can provide useful frameworks. Soil loss tolerance refers to the maximum soil loss that can occur from a given land without leading to degradation of the soil (Hurni, 1983; Morgan, 2005). For conservation planning, soil loss tolerance values can be set at rates of soil formation; unfortunately, however, it is not practically possible to determine the rate at which soil loss equals the rate of soil formation. Different values of soil loss tolerance have been proposed by different authors (Morgan, 2005), but a mean annual soil loss of $11\,t\,ha^{-1}$ is generally considered acceptable while it may be as low as $2\,t\,ha^{-1}$ in sensitive areas (Hudson, 1981). The other important concept is that of critical soil loss, which refers to a value from which it is no more possible to reduce soil erosion no matter what conservation measure will be used. In such cases, the available option for sustainable land use will be to change the land-use type itself; for instance, from cropland to forest.

Finally, the study demonstrates that the USLE together with satellite remote sensing and geographical information systems provide useful tools to estimate erosion hazard over watersheds and facilitate sustainable land management. It has given a fairly reliable estimation of soil loss and delineation of erosion-prone areas. But it is important to note that the estimated soil loss rates are not precise because of the well-known limitations of the model (cf. Morgan, 2005). For instance, the basic equation implies that each factor is derived independently, while in reality, there is obvious interdependence between the variables. The practical problems in estimating USLE factor values in the eastern and western African contexts have been discussed by Mati and Veihe (2001). Morgan (2005) notes that USLE was developed as ‘a tool to guide soil conservation planning, and not for use as a research technique’. In this sense, the results of this study and the method used are quite useful given the fact that measured data are unavailable, and physically based distributed models are difficult to apply due to lack of input data, which is the case in many developing countries. On the other hand, obtaining the same information by field surveys would take a long time and considerable human resources. The method can thus be applied in other watersheds for assessment and delineation of erosion-prone areas for prioritization of micro-watersheds for conservation intervention and enable efficient use of limited resources.

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