Climate change and land degradation in Africa: a case study in the Mount Elgon region, Uganda

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(Received 5 August 2013; final version received 16 December 2013)

The aim of this study is to estimate and compare soil erosion, in the Mount Elgon region, eastern Uganda, during the last decade. Possible trends and changes in erosion are linked to precipitation/climate change as well as changes in land cover. Two different versions of the Revised Universal Soil loss Equation (RUSLE) are implemented and compared, one using slope length and the other using flow accumulation to estimate the slope length and steepness factor ($L_S$). Comparisons of the modeled soil erosion vs. field data indicate that RUSLE based on flow accumulation is preferable. The modeling is carried out for the years 2000, 2006, and 2012, and is based on ASTER remotely sensed data, digital elevation models, precipitation data from the study area, as well as existing soil maps. No significant trends in estimated soil erosion are found to be present during the last decade. Over exploitation of land is probably compensated by improved agricultural management and no significant increase in precipitation. Even if there are reports of more intense and increasing amounts of rainfall in the area, this could not be verified, neither through the analysis of climate data, nor by trends in the estimated soil loss.

\textbf{Keywords:} soil erosion; revised universal soil loss equation (RUSLE); ASTER; Uganda; climate change

1. Introduction

1.1 Background

As one of the most important basic natural resource, land relates to almost all human activities directly or indirectly, and is crucial for sustaining livelihoods in many sub-Saharan African (SSA) countries. Rational utilization of the land resource has been treated as the key factor in the development pathways of many SSA countries. However, land degradation is one of the major and widespread environmental threats both in the past and present years (1). Furthermore, soil erosion is regarded as the most serious form of land degradation around the world, especially in developing countries like Uganda, China, and India, as well as some developed countries like Spain (2–4). In order to meet their livelihoods, address the economic stress, and accelerate development, some people and development actors in the developing countries utilize land and soil resources in unsustainable and irrational ways as manifested by overgrazing, destruction of forest for urban extension, heavy intensity and unscientific agricultural activities, and land use changes in high frequency (5). As a result, soil erosion becomes a serious issue, which negatively impacts the soil quality reducing agricultural efficiency, worsening water quality, causing flooding and debris flow, and habitat destruction (6).

Mountains ecosystems are considered as one of the most significant ecosystems, providing huge amount of benefits to humans both in natural and economic aspects via various ecosystem services and products. Nevertheless, unsustainable and unscientific land use practices and improper land management cause serious soil erosion in mountain regions. More and more studies are carried out focusing on mountainous areas in order to get better understanding of why the phenomenon happens and what could be done to solve the problems (7–10). In recent years, governments started to pay attention to sustainable agriculture and development. As a result, many environment and land degradation assessment policies were announced and published, which pointed out that soil erosion and land degradation in mountain areas are being increasingly regarded as more serious than in other ecosystems (11–14). One of the major reasons for this is land use changes in high frequency, not only modifications but also conversion of the land cover, which has a negative impact on the environment, especially replacement of forest area by agriculture fields due to the pressure of population (15, 16). The other major reason is the irregular terrain and topography in the mountain areas, which means that slope diversity and heterogeneity are significant factors for the intensity of soil erosion (17). Combined with rapid climate variability and changes, mountain ecosystems are one of the most sensitive ecosystems to climate change. The variation in rainfall pattern significantly impacts the runoff.

In a study by Knapen et al. (17), carried out on Mount Elgon in Uganda, it was observed that East Africa has severe land degradation around the highlands.
They also pointed out that the high vulnerability of the slopes and the high annual precipitation, including steep slopes and high weathering rates, could be important reasons for the serious soil erosion in this area. In the end of their report, human activities due to high population density and associated pressures were considered as the most important factor for land degradation. Another study that focused on land use changes around Mount Elgon done by Mugagga et al. (8) indicates that population pressure in the Mount Elgon region has resulted in large areas of forest being replaced by agriculture fields without sustainable management. These unsustainable and unscientific land use practices have caused a lot of environmental problems exemplified by landslides, high erosion rates, and stream pollution loading on Mount Elgon. It is however, predicted that activities supporting forest replacement by cropland and grazing land will continue until 2032 (18).

East Arica has been emphasized as the focal point of soil erosion. Better management and sustainable development measures have to be worked out and implemented.

There are two main approaches to study soil erosion, depending on spatial and temporal scales (1). One entails on-site measurements, which involves performing irrigation experiments on small-scale plots. The other is off-site quantification through modeling, which can be applied to reveal potential patterns of soil erosion, or evaluate the soil erosion on a large scale. According to the study by Rafaelli et al. (19), if data from field measurements are lacking and/or sparse due to costs of manpower and time constraints, off-site modeling techniques are preferable. Lack of data is apparent in the Mount Elgon region, partly due to climatic conditions, with a high cloud cover, and partly due to the location, with steep slopes and a sparse road network making it difficult and expensive to carry out field measurements.

In order to build the quantification model, as many as possible of the criteria that influence soil erosion should be taken into consideration. The Revised Universal Soil Loss Equation (RUSLE) is a widely used soil erosion intensity evaluation model, modified and improved from the Universal Soil Loss Equation (USLE), developed by Wischmeier (20). There are several factors included in this model, such as rainfall erosivity, soil erodability, slope length and steepness factor, cover management factor, and conservation practice factor. RUSLE can be treated as a kind of multi-criteria analysis, since the results are calculated according to the influencing factors. GIS technology is thus appropriate due to its powerful multi-criteria processing and calculation capability (21, 22). Moreover, in many conclusions of previous studies, highly significant spatio-temporal phenomena or changing patterns were revealed by applying GIS and remote sensing-based soil erosion/land degradation modeling (23, 24). Long-term studies can be performed, and the changes in soil erosion intensity patterns can be shown and analyzed using these methods. Hence, evaluation and prediction are possible to carry out much easier and faster than before to address the hazards caused by soil erosion.

1.2. Aims and objectives

The overall aim of this study is to explore possible trends in climate conditions as well as soil erosion in the Mount Elgon region in Uganda during the last decade.

The original RUSLE model structure is compared with an updated RUSLE model, where the slope length factor is replaced by drainage area. If the results of the updated RUSLE gives better results, then the modified parameters would be more appropriate for the study area conditions.

The first specific aim is thus to produce high-accuracy soil erosion estimates for the study area. Second, possible climate and soil erosion intensity trends from 2000 to 2012 are discussed. These aims are addressed through the following objectives:

- To understand the influencing factors in the RUSLE model and the basic usage of the model by reviewing literature and previous studies.
- To perform the two different model calculations for the years 2000, 2006, and 2012 in order to estimate soil erosion and create soil erosion intensity maps.
- To compare the accuracy of the two methods by using field measured data.
- To analyze the soil erosion intensity between 2000 and 2012 as impacted by climate and land use change.

1.3. Research questions

- The major questions which this study addresses are:
  - Are there indicative signs of climate change in the study area?
  - Is the updated version of RUSLE, using flow accumulation instead of slope length, more preferable?
  - How much soil was lost each year during the last decade in the selected micro-catchment on Mount Elgon?
  - What is the soil erosion pattern from the year 2000 to 2012?
  - Why do possible trends and patterns occur, and what can be done to avoid or mitigate soil erosion in the future?

1.4. General methodology

In order to answer the research questions, several steps are undertaken. Firstly, relevant literature is reviewed, including basic information about Uganda and the certain study area, the factors in the RUSLE model, and
knowledge about previous use of the model. Secondly, referring to the factors in the model, the data-sets of the study area are collected from various sources. Digital elevation models (DEM), satellite images, climate data for rainfall, and soil classification maps are used. Afterwards, by applying the RUSLE model and the updated RUSLE model, the result of soil erosion intensity of the target years are estimated and presented in tabular formats as well as maps. Finally, an evaluation is performed to assess the accuracy of the results derived using the original RUSLE structure and the modified structure. A statistical analysis is carried out in order to explain the possible soil erosion patterns and trends, as well as the climatic influence.

2. Study area
2.1. Location
The study area is located on the Ugandan territory of Mount Elgon. Mount Elgon is a transboundary mountain which lies on the border of western Kenya and eastern Uganda. The mountain is the largest and oldest extinct volcano from Pliocene age in East Africa. The elevation is about 4322 m (25). The actual study area constitutes a part of Manafwa catchment, lying on the western side, as illustrated in Figure 1. The map shows the position of the study area. It is located between latitude 0.893° and 1.084°, and longitude 34.056° and 34.384° in the WGS84 coordinates system. The total coverage of the study area is 365 km².

2.2. Topography
Several studies point out that the geomorphology of the Mount Elgon region is dominated by volcanism (17, 26). The elevation in the study area varies between 1084 and 2455 m above sea level. Due to mountainous characteristics, the variation of the slope is large. The largest slope is 50 degree, 48% of the area have slopes less than 5 degrees, 18% of the area have slopes from 5 to 10 degrees, 23% of the area have slopes between 10 and 20 degrees, and 11% of the study area have slopes exceeding 20 degrees.

2.3. Climate
The climate of the Mount Elgon region can be defined as humid subtropical. It is dominated by seasonally alternating moist southwesterly and dry northeasterly air streams. The mean annual air temperature is about 23 °C. Moreover, the average minimum and maximum temperature is 15 °C and 28 °C, respectively. The warmest months in the year are from January to March and the coolest months are from July to August. The onset and cessation of rainfall months are March and December, respectively. The mean annual precipitation is generally around 1500 mm (7). The precipitation in the Mount Elgon region shows a weak bi-modal pattern. The rainfall differences are mostly influenced by orographic conditions, altitude, and location.

2.4. Soil
Generally, the soil structure of Mount Elgon is deep and derived from volcanic ash as the product of a single weathering cycle (11). A significant characteristic pointed out by Isabirye (27) is that the soils of this area are highly variable because of the structure of the carbonatite dome. In a study by Bamutaze (28), three main sources of the soil types in Mount Elgon are stated. First, volcanic ash and agglomerates found under volcanic mountains and hills and their pediments have contributed to the formation of the soils. Second, some of the soils are derived from metamorphic rocks, which are the degraded Gondwana surface. Thirdly, another part of soils is derived from mixed volcanic-metamorphic rocks.

2.5. Vegetation and land cover
The distribution of vegetation in Mount Elgon region is influenced by many physical and anthropogenic factors, such as elevation, aspect, soil, climate, and land use practices (29). Generally, four different broad vegetation communities can be observed. Mixed montane forest can be found up to elevation of 2500 m, bamboo and canopy montane forest can be found from 2400 to 3000 m, and moorland can be found above 3500 m (30). However, the natural vegetation is heavily influenced by human activities. Because of the pressure from the rapidly increasing population, natural vegetation is damaged by intense agriculture and grazing activities, especially in the area below 2200 m. Agriculture lands occupy 47% of the landscape, and grassland areas cover 22% (31). This potential damage of the ground cover vegetation, of course, can lead to an increased risk of soil erosion.

2.6. Population and land use
The estimated population density of Manafwa catchment region varies between 250 and 700 persons per square kilometer (7). The land use types in the Mount Elgon region are classified as crop lands, secondary forest, natural forest, bare land, and built-up areas. Agriculture lands are the most common land use type across this area and agriculture activities are extremely frequent (31). The agriculture activities are mostly carried out below the elevation of 2000 m. Montane farming system and smallholdings are the most common forms of agriculture in this region (32). Due to low efficiency in the agriculture and the huge pressure caused by the population, the crop lands are encroaching upon higher mountain areas, which are impacting the natural forest area. Mugagga et al.(8) note that the most significant land use changes are the conversion from natural forest to other land use types, especially crop lands and grazing lands. This kind of land management can easily lead to increased land degradation and soil erosion.
3. Materials

3.1. Digital elevation model

The terrain data required for the modeling (flow length, flow accumulation, slope gradient, etc.) were all extracted from a DEM. This original DEM was interpolated by using a 10-m resolution contour map, provided by the Department of Mapping and Surveys for Uganda. The extracted raster DEM was generated in ArcGIS 10 by using the inherent protocols. It is under WGS 1984 spatial reference coordinate system and projected to UTM Zone 36 N. The spatial resolution is 25 m. The elevation range of the Mount Elgon region is from 1041 to 4301 m. The DEM data were used to estimate the slope gradient, flow direction, catchment area, slope length, and flow accumulation for the study.

3.2. Climate data

The climate data are from Bamutaze (28), collected from four different climate stations: Bududa, Bulucheke, Bulubwale, and Nabumali. The rainfall data are obtained from the Department of Meteorology of Uganda. The climate data include precipitation, relative humidity, solar intensity, wind speed, and temperature. All the data are provided in DBF format, which can be read as tables by ArcGIS 10 or Excel. The position of the climate stations and the location of the study area are shown in Figure 2.

Only precipitation is significant for this study. The data are distributed in daily form. The rainfall data in millimeter for the target years 2000, 2006, and 2012 were extracted from a larger data-set. The precision of this data-set is 0.01 mm. The rainfall erosivity factor was estimated by interpolating the values from the climate stations.

Figure 1. Location of the study area.
3.3. Soil data

Due to limitations in the available soil data, a combination of two different types of soil data is used in this study. Two soil maps which contain different soil types as attributes are used (28). The soil types are in the Food and Agriculture Organization classification system. One soil map contains more detailed soil information of the area located in the southwestern part of the Mount Elgon region. Unfortunately, there are some gaps in this dataset. In order to fill these gaps, another Uganda national-level soil map with lower resolution is used. As a result, a full soil map of southwestern Mount Elgon was generated to aid the estimation of the soil erodability factor.

3.4. Satellite remote sensing data

The used ASTER satellite images are from the summer period of the years 2000, 2006, and 2012. The spatial resolution of the satellite images used is 15 m. All images were geo-referenced under the WGS84 coordinate system. Detailed information about the used ASTER images is shown in Table 1. The three satellite images used are expected to be from the same date. However, due to heavy cloud cover in the Mount Elgon region during summer time this requirement is difficult to fulfill. The data used in this study are the best combination that can be found.

There are three bands in the downloaded data, BAND1, BAND2, and BAND3 N. The corresponding wave lengths of the three bands are shown in Table 2.

In the downloaded data, the digital values for Green, Red, and Near-infrared band were interpreted following the spectral reflectance characteristics. That means the satellite images can be used for Normalized Difference Vegetation Index (NDVI) calculation directly in the further processing stage. The NDVI data indicate the land cover environment. NDVI was thus used to estimate the cover management factor which is one of the components in RUSLE model.

3.4.1. Field data

Field measurements of soil erosion collected and presented by Bamutaze (28) are used in this study. Soil loss was measured in field at 11 different locations in the study area. All measurements were carried out by the use of sediment traps in open streams.

4. Methodology

4.1. The RUSLE model

The RUSLE soil erosion model is used to estimate soil erosion intensity in a catchment. The RUSLE model is based on the USLE erosion model structure which was

Table 1. Data about the ASTER images used in the study.

| Product ID | Time     | Central coordinates | Cloud coverage (%) | Bands          |
|------------|----------|---------------------|--------------------|---------------|
| Prodat011  | 2012/6/27| Lat: 1.107, Long: 34.261 | 20                 | Band1, Band2, Band3 N |
| Prodat012  | 2006/8/30| Lat: 1.111, Long: 34.236 | 13                 | Band1, Band2, Band3 N |
| Prodat013  | 2000/9/30| Lat: 1.124, Long: 34.144 | 4                  | Band1, Band2, Band3 N |
developed by Wischmeier and Smith (33), and improved and modified by Renard et al. (34). Five parameters are used in the RUSLE model to estimate soil loss. They are rainfall erosivity (R), soil erodability (K), slope length and steepness factor (LS), cover management factor (C), and conservation practice factor (P). Referring to the RUSLE model, the relationship is expressed as:

\[ A = \frac{R}{C^2} \cdot \frac{K}{C^2} \cdot \frac{LS}{C^2} \cdot \frac{C}{P} \]  

(1)

where \( A \) (t ha\(^{-1}\) y\(^{-1}\)) is the estimated spatial average of total soil loss per year; \( R \) (MJ mm ha\(^{-1}\) h\(^{-1}\) y\(^{-1}\)) is the rainfall erosivity factor; \( K \) (t ha h ha\(^{-1}\) MJ\(^{-1}\) mm\(^{-1}\)) is the soil erodability factor; \( LS \) is the slope length and steepness factor (dimensionless); \( C \) is the land surface cover management factor (dimensionless); and \( P \) is the erosion control conservation practice factor (dimensionless).

The methods and formulas for estimating each of the parameters in the RUSLE model are mainly based on three previous studies: Bamutaze (28), Pilesjö (35), and Prasannakumar et al. (10). The work flow is shown in the flow chart in Figure 3.

4.2. Rainfall erosivity factor (R)
The rainfall erosivity factor indicates the erosive force of a specific rainfall (10). The relationship between rainfall erosivity and rainfall developed by Wischmeier and Smith (33) and modified by Arnoldus (36) was used to convert the monthly rainfall values to rainfall erosivity. The calculation was as follows:

\[ R = \sum_{i=1}^{12} 1.735 \times 10^{1.5 \cdot \log_{10} (P_i^2) - 0.08188} \]  

(2)

where \( R \) is the rainfall erosivity value in MJ mm ha\(^{-1}\) h\(^{-1}\) y\(^{-1}\), \( P_i \) is the monthly rainfall of the \( i \)-th month \((i = 1, 2, \ldots, 12)\) in mm, and \( P \) is the annual rainfall in mm.

Erosivity values between the rainfall stations were estimated by the use of inverse distance weighting (IDW) interpolation. The rainfall erosivity of the study area for the years 2000, 2006, and 2012 varies between 897 and 2813 MJ mm ha\(^{-1}\) h\(^{-1}\) y\(^{-1}\). The highest and lowest values both appear in the year 2000. The southwestern part of the study area always has the highest rainfall erosivity values.
Pileşjö (35) estimates soil erodibility values using the color of the soils according to Bono and Seiler (38), Bono and Seiler (39), and Weigel (40). Table 3 shows the K-value for different soil colors.

The five different soil types were assigned K-values according to the colors of the soils. The colors for the five different types of soil were obtained from ISRIC (41). For the Ferralsols soil there is no detailed subclass classification in the ISRIC document. The color is set to either red or yellow. The K-values for the two Ferralsols were thus set using the mean K-value of red and yellow color. The K-values of the five types of soil are listed in Table 4.

### 4.4. Slope length and steepness factor (LS)

The slope and steepness factor (LS) is a combination of slope steepness and slope length, to a high degree affecting the total sediment yield from site. It is considered to be one of the most challenging factors to derive (42). Prasannakumar et al. (10) claim that generating the LS-factor also captures factors like compaction, consolidation, and disturbance of the soil.

In this study, two different parameters are used to estimate the LS-factor, flow length and flow accumulation. Both flow length and flow accumulation can be used to estimate the contribution of upstream cells in a DEM to downstream cells. Flow length, also called slope length, helps in estimating the water flow along lines while flow accumulation is based on drainage area. For a specific cell, the flow accumulation is estimated based on the upslope area and not just along flow lines.

The LS factors were estimated by applying the equation proposed by Moore and Burch (43, 44). The relationship is as follows:

$$LS = \left( \frac{\text{Flow length (or Flow accumulation)}}{\text{Cellsize}} \right)^{0.4} \times \left( \frac{\sin\text{slope}}{0.0896} \right)^{1.3}$$

where LS is the combination of slope length and steepness, Flow accumulation or Flow length is the accumulated upslope contribution to a cell, Cell size is the resolution of the raster image, and Sin slope is the sinus value of the slope in degrees.

The estimated LS values based on slope length, varying between 0 and 184, are presented in Figure 4.

The estimated LS values based on flow accumulation, varying between 0 and 95, are presented in Figure 5.

### 4.5. Cover management factor (C)

The cover management factor represents the effect of plants, crop sequence, and other soil cover surface on soil erosion. The value of C-factor is defined as the ratio of soil loss from a certain kind of land surface cover condition (33).

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Table 3. The K-value for different soil colors.

| Color     | K-value |
|-----------|---------|
| Black     | 0.15    |
| Brown     | 0.2     |
| Red       | 0.25    |
| Yellow    | 0.3     |

Table 4. The colors and corresponding K-values for the soils in the study area.

| Soil type                  | Color               | K-value |
|----------------------------|---------------------|---------|
| Nitisols                   | Red                 | 0.250   |
| Gleysols                   | Black               | 0.150   |
| Petric plinthols (Acric)   | Red                 | 0.250   |
| Lixic ferralsols           | Red or Yellow       | 0.275   |
| Acric ferralsols           | Red or Yellow       | 0.275   |

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Figure 4. LS-factor estimated using flow length.

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According to Prasannakumar et al. (10), the NDVI can be used as an indicator of the land vegetation vigor and health. In addition, Karydas et al. (45) and Tian et al. (46) state that due to the variety inland cover patterns, satellite remote sensing data can act as an extremely important role to estimate the $C$-factor.

In this study the original satellite images from the year 2000, 2006, and 2012, with reflectance values in the green, red, and near-infrared bands, were converted to NDVI for the corresponding years.

After calculating the NDVI, the $C$-factor can be estimated by applying the relationship used in Zhou et al. (47) and Kouli et al. (48):

$$C = \exp\left(\frac{-\alpha \times \text{NDVI}}{\beta - \text{NDVI}}\right)$$  \hspace{1cm} (3)

where $C$ is the calculated cover management factor, NDVI is the vegetation index, and $\alpha$ and $\beta$ are two scaling factors. van der Knijff et al. (49) suggest that by applying this relationship better results than using a linear relationship can be obtained. They suggest the values for the two scaling factors $\alpha$ and $\beta$ to be 2 and 1, respectively.

Because of the cloud cover in the rainy season, the quality of the satellite images is limited, which may cause some uncertainties in the results. In order to remove cloudy areas the clouds and the shadow of clouds were classified using unsupervised classification and the spectral bands green, red, and near infrared. The number of unsupervised classes was set to 15. The classes, automatically clustered by the unsupervised classification tool in ArcGIS, were finally grouped to construct cloud layers. In the $C$-factor maps and the final results the cloud areas are shown as black with no data. The cloud (and cloud shadow) areas for the three different years (2000, 2006, and 2012) were 4.92, 0.59, and 12.38%, respectively. Estimated $C$-factor values varied between 0.00008 and 0.66. The spatial distribution of the $C$-factor for the different years is presented in Figures 6–8.

Figure 5. $LS$-factor estimated using flow accumulation.

Figure 6. $C$-factor of the study area in the year 2000.
4.6. Conservation practice factor (P)

The conservation practice factor (P) is also called as support factor. It represents the soil loss ratio after performing a specific support practice to the corresponding soil loss, which can be treated as the factor representing the effect of soil and water conservation practices (34, 50). The range of P factor varies from 0 to 1. The lower the value is, the more effective the conservation practices are.

In this study this conservation practice factor was assigned the maximum value of one (1) across the entire study area. The reason for this is that there are no significant conservation practices in the study area. In Manafawa, most of the conservation practices are tree planting, and can thus be considered to influence the cover management factor (C) (28).

5. Results

In order to estimate annual soil loss, the five factors were multiplied according to the relationship in RUSLE model. In total six layers with annual soil loss were computed, two for each year, one using flow length, and one using flow accumulation. The soil loss was classified into soil erosion risk maps with five different soil erosion risk levels according to Bamutaze (28). The thresholds for each of the risk levels are presented in Table 5.

5.1. Soil erosion risk based on flow length method

In general, the soil erosion risk maps obtained by flow length method have relatively high annual soil loss values. Exploring the maps (Figure 9) it can be concluded that more than 50% of the area is exposed for very high erosion risk.
For the year 2000, Figure 9 illustrates the estimated erosion risk. The soil loss estimated by the flow length method in this year varies between 0 and 4995 t ha\(^{-1}\) y\(^{-1}\), with an average value of 364 t ha\(^{-1}\) y\(^{-1}\); 62% of the area has a very high erosion risk, 17% has high risk, 6% has moderate risk, 6% has low risk, and only 2% has very low risk of soil erosion.

For the year 2006, the estimated annual soil loss varies between 0 and 4698 t ha\(^{-1}\) y\(^{-1}\), which is similar to the result of year 2000. However, the mean value is 231 t ha\(^{-1}\) y\(^{-1}\), which is much lower than that of 2000. About 55% of the area has very high erosion risk, 16% has high risk, 20% has moderate risk, 7% has low risk, and only 2% has very low risk of soil erosion.

For 2012, the estimated soil loss varies between 0 and 6053 t ha\(^{-1}\) y\(^{-1}\). The value 6053 t ha\(^{-1}\) y\(^{-1}\) is higher than the maximum values for 2000 as well as 2006. Referring to Figure 12, the area covered by moderate erosion risk is the highest (32%), followed by very high risk (28%), low and high risks (16%), and very low risk (8%).

### Table 5. Categorization of soil erosion risk.

| Erosion risk | Threshold (t ha\(^{-1}\) y\(^{-1}\)) |
|--------------|-----------------------------------|
| Very low     | Soil Loss \(\leq 2\)              |
| Low          | \(2 \leq\) Soil Loss \(\leq 10\) |
| Moderate     | \(10 \leq\) Soil Loss \(\leq 50\) |
| High         | \(50 \leq\) Soil Loss \(\leq 100\) |
| Very high    | Soil Loss \(\geq 100\)             |

For the year 2000, Figure 9 illustrates the estimated erosion risk. The soil loss estimated by the flow length method in this year varies between 0 and 4995 t ha\(^{-1}\) y\(^{-1}\), with an average value of 364 t ha\(^{-1}\) y\(^{-1}\); 62% of the area has a very high erosion risk, 17% has high risk, 6% has moderate risk, 6% has low risk, and only 2% has very low risk of soil erosion.

For the year 2006, the estimated annual soil loss varies between 0 and 4698 t ha\(^{-1}\) y\(^{-1}\), which is similar to the result of year 2000. However, the mean value decreases to 231 t ha\(^{-1}\) y\(^{-1}\), which is much lower than that of 2000. About 55% of the area has very high erosion risk, 16% has high risk, 20% has moderate risk, 7% has low risk, and only 2% has very low risk of soil erosion.

### 5.2. Soil erosion risk based on flow accumulation method

Generally, the absolute values of annual soil loss using the flow accumulation are much smaller than the results estimated by using flow length method. The results also coincide better with field data, and are thus more reliable.

In the year 2000 the highest estimated soil loss is 1198 t ha\(^{-1}\) y\(^{-1}\) (Figure 10). The mean value for the whole study area is 103 t ha\(^{-1}\) y\(^{-1}\); 31% of the study area is classified to have a moderate soil erosion risk. Higher and much higher risks are allocated to 19 and 30%, respectively, while 14% of the area has low risk of erosion and 6% very low risk.

The estimated soil erosion risk map for the year 2006 is shown in Figure 11. In this year, the estimated annual soil loss varies between 0 and 1129 t ha\(^{-1}\) y\(^{-1}\) which is almost the same as for the year 2000. However, the mean value decreases to 67 t ha\(^{-1}\) y\(^{-1}\), which is the lowest estimated mean soil loss value of all the results. About 39% of the area has moderate risk of soil erosion, high and very high risks are allocated 19% each, 16% of the area has low risk, and 7% has very low risk of soil erosion.

For 2012 the estimated soil loss varies between 0 and 1454 t ha\(^{-1}\) y\(^{-1}\). The value 1454 t ha\(^{-1}\) y\(^{-1}\) is higher than the maximum values for 2000 as well as 2006. Referring to Figure 12, the area covered by moderate erosion risk is the highest (32%), followed by very high risk (28%), low and high risks (16%), and very low risk (8%).

### 5.3. Comparison of the two modeling methods

Based on the results obtained by the flow length and flow accumulation methods, a comparison of accuracy was carried out in order to judge which of the two methods gave better and more accurate result. The comparison was made from two aspects.

First, from the cartographic point of view, the estimated result maps obtained by using the flow length method have large areas assigned high or very high soil
erosion risk levels. The areas with very high erosion risk level are 62%, 55%, and 56% for the year 2000, 2006, and 2012, respectively. When comparing with field visits and interviews with farmers this is unrealistic. Additionally, the classification method used to generate the soil erosion risk maps is referring to a published study by Bamutaze (2006), reporting lower soil erosion risks in the region. Altogether, this indicates that the results obtained by using the flow accumulation method is better.

Second, according to the results reported by Bamutaze (2006), from a nearby area in the 1990s, the average annual soil loss value was 43 t ha\(^{-1}\) y\(^{-1}\), with maximum value of 585 t ha\(^{-1}\) y\(^{-1}\) on a cell level, and the highest potential erosion value reached up to 778 t ha\(^{-1}\) y\(^{-1}\). In the study presented in this paper, the results obtained by using the flow accumulation method gave average annual soil loss values of 103 t ha\(^{-1}\) y\(^{-1}\), 67 t ha\(^{-1}\) y\(^{-1}\), and 101 t ha\(^{-1}\) y\(^{-1}\), with highest values of 1198 t ha\(^{-1}\) y\(^{-1}\), 1129 t ha\(^{-1}\) y\(^{-1}\), and 1454 t ha\(^{-1}\) y\(^{-1}\) for the three years 2000, 2006, and 2012, respectively. These estimates are much closer to the previous study than the results obtained by using the flow length method.

To conclude, the results obtained by using the flow accumulation method seem more accurate and reliable than those obtained by using flow length. Thus, further discussion on the soil erosion trends and the relationships between soil erosion and precipitation/climate and land cover is based on the results obtained by the flow accumulation method.
6. Discussion

6.1. Uncertainties and limitations

In general, due to specific characteristics of the study area, a mountainous area located in the Mount Elgon region, finding the data which fulfill the requirements of RUSLE modeling is very difficult. In this study, most of the data are provided by local departments and researchers except for the ASTER remote sensing data. Due to the lack of data, the time series study was only carried out for the three target years 2000, 2006, and 2012.

In the result maps, some of the estimated soil loss values are very high, reaching 1454 t ha\(^{-1}\) y\(^{-1}\) using flow accumulation, and 6053 t ha\(^{-1}\) y\(^{-1}\) using flow length. The original DEM data are an interpolated 25-m resolution raster map based on digitized contour lines. Due to the 25-m resolution, some sinks and breaks are removed from the DEM. This results in exaggerated estimations of flow lengths as well as flow accumulation, with corresponding high LS values.

Regarding precipitation, only data from four rainfall stations in the region were available for the three years 2000, 2006, and 2012. The precipitation data for the entire study area were generated by running IDW interpolations with data from these four stations, which is not preferable. Moreover, the location for the four climate stations used for interpolation is clustered in the eastern part of the study area. One can thus expect the interpolated precipitation values to be more accurate in the eastern part of the study area.

Five types of soil are detected in the study area, based on a soil map of questionable quality. In Uganda, soil mapping is still at coarse scale, which makes it a challenge to get high-quality data. Additionally, the method used to estimate the K-factor is based on the color of a particular type of soil, which can be considered as a rough estimation method. In the study done by Xu et al. (1), a more professional K-factor estimation method, referring to the study by Sharpley and Williams (31), is presented. However, in order to apply this method, more detailed soil parameters not available in this study are required, like the subsoil sand fraction, the silt fraction, the clay fraction, and the topsoil carbon content.

There are also uncertainties in the cover management factor that was estimated by the use of ASTER satellite images. There are mainly two sources generating the uncertainties, one related to the temporal distribution of the satellite data and the other related to cloud cover.

The satellite data are supposed to be from the same month and in summer time. The reason for this is that not only this period has the most vegetation cover, but also that it is the most serious erosion period due to rain-fall in the rainy season. However, the rainy season and the mountainous climate conditions result in extremely cloudy weather. It was impossible to find satellite data from the same month for different years. For the target years 2000, 2006, and 2012, the images used in this study are from September 30, August 30, and June 27, respectively. We can thus expect more uncertainty in the image from July 2012. The land cover situation two month earlier than the other two target years may be significantly different.

The uncertainties relating to clouds are always a big problem when using remotely sensed data. In this study, all images are influenced by cloud cover. In the year 2012, the cloud cover is more than 12%. Because the shadow of the cloud has a negative effect on the NDVI and the estimated C-factor values, the cloud area was over-classified when carrying out the classification. The classified cloud area also contains cloud shadow. Even though an over-classification was performed, some noise pixels remained. In order to reduce their influence, a low pass 3 × 3 average filter was used to smooth the C-factor data layer.

Figure 12. Soil erosion risk map obtained by flow accumulation method for the year 2012.
6.2. Soil erosion trends related to precipitation and land cover changes

Mean annual precipitation and mean \textit{R}-factor of the study area for the three years are presented in Figure 13 as blue and red lines, respectively. From 2000 to 2006, the mean annual precipitation decreases from 1290 mm to 1200 mm. Then the precipitation increases from 1200 mm to 1249 mm from 2006 to 2012. The mean annual precipitation for 2012 is approximately the same as for the year 2000. The \textit{R}-factor shows a similar trend. However, the mean \textit{R}-factor value in 2012 is significantly higher than during the year 2000 (1776 and 1448 MJ mm ha\(^{-1}\) h\(^{-1}\) y\(^{-1}\)). This means that the rainfall in 2012 had the biggest effect on soil erosion among the three target years.

Regarding land cover, mean NDVI was used as the detector for land cover changes. As illustrated in Figure 14, mean NDVI values increases from 0.56 to 0.59 during the years 2000 to 2012. The increasing trend is considered as very weak.

From the year 2000 to 2006, 57% of the land area has an increasing NDVI. This area is mainly located in the western part of the study area. The area with decreasing NDVI (47%) appears mainly in the south and east. From 2006 to 2012, an increasing trend is seen with an increasing coverage percentage of 58%. The increasing NDVI is still located in the western part of the study area. The decreasing NDVI is mainly in the northeast. Comparing the year 2000 and 2012, 64% of the land has an increasing NDVI. Even if the analysis is influenced by cloud cover and not significant, one can see clear indications that most of the western part of the study area has got more vegetation cover during the last decade. However, a regular polygon located in the southwest corner has a large decrease in vegetation cover, may be caused by artificial activities such as urban construction, or agriculture land conversion.

Soil erosion changes and trends can be explored in Figure 15. The estimated soil erosion decreases between 2000 and 2006, and increases between 2006 and 2012. This “trend” is similar to the precipitation trend discussed above. There seems to be no significant relationship between land cover changes and soil erosion on the study area scale.

7. Conclusions

Based on the results of this study we can conclude that, for the study area in the Mount Elgon region, Uganda:

(1) No significant trends in rainfall during the last decade are found.
(2) The modified RUSLE model, using flow accumulation instead of slope length, is preferable when estimating risk of soil erosion.
(3) The risk of soil erosion is not significantly different in 2012 compared to year 2000.
(4) No specific trends or patterns in soil loss, precipitation, and land cover have been found.
Notes on Contributors

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