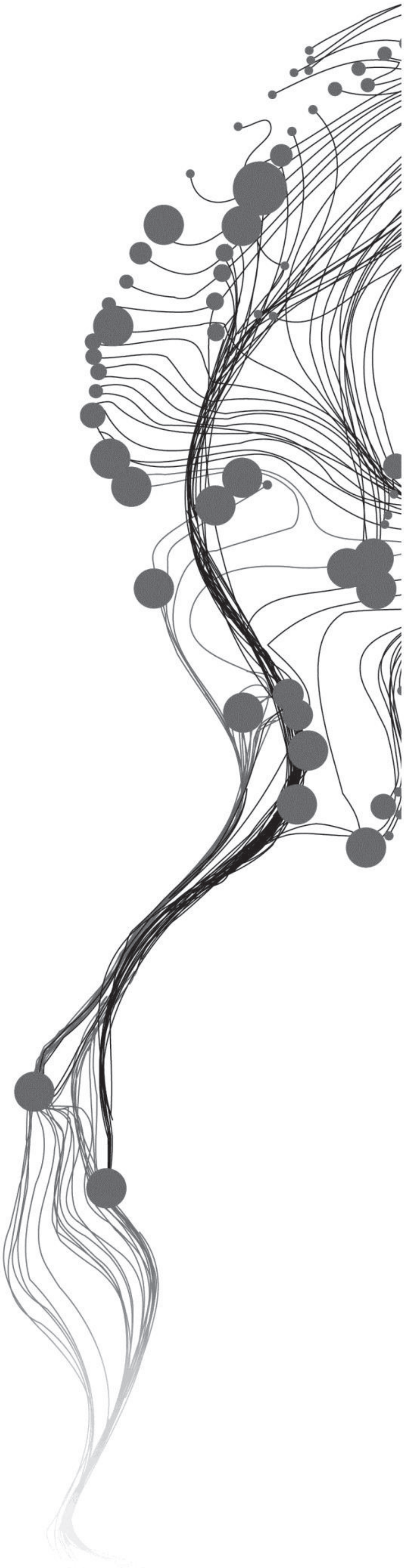
Estimating Patterns of Potential Soil Erosion for Eritrea over Time and Space through Remotely Sensed Rainfall Intensity and Vegetation Indices

Habtom Tsegay Debesay

SUPERVISORS:
Dr. Ir. A. Vrieling
Dr. Ir. C.A.J.M. de Bie



Estimating Patterns of Potential Soil Erosion for Eritrea over Time and Space through Remotely Sensed Rainfall Intensity and Vegetation Indices

HABTOM TSEGAY DEBESAY

Enschede, the Netherlands, February, 2013

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: [Natural Resources Management]

SUPERVISORS:
Dr. Ir. A. Vrieling (First supervisor)
Dr. Ir. C.A.J.M. de Bie (Second supervisor)

THESIS ASSESSMENT BOARD:
Prof. Andrew Skidmore (Chair)
Dr. Ir. B.G.J.S. Sonneveld (External Examiner, Centre for World Food Studies (SOW-VU), Vrije Universiteit Amsterdam)
Dr. Ir. A. Vrieling (First supervisor)
Dr. Ir. C.A.J.M. de Bie (Second supervisor)

ABSTRACT

Soil in Eritrea is losing productivity because of severe erosion. The numerous small-scale peasants (around 80% of the population) are highly affected their livelihood by this process. Soil erosion assessment can help to make spatial plans for erosion mitigation measures by targeting priority areas. Multi-temporal satellite products can provide important input to such assessments. Given the erratic nature of the erosion processes, it is important that information derived from satellites accounts effectively for the variability of erosion controlling factors.

Erosion processes occur on areas with erodible soils and sloping terrain when high-intensity rainfall coincides with limited vegetation cover. Timing of erosion events has implications on the selection of satellite imagery, used to describe spatial patterns of protective vegetation cover. Two of the most dynamic and time-dependent factors for soil erosion estimation are rainfall erosivity and vegetation cover. To estimate when during the year soil erosion risk is highest, coarse-resolution 3-hourly rainfall intensity data from TRMM were combined with 10-daily SPOT VEGETATION NDVI imagery. Monthly and annual erosivity estimates were derived from the 3-hourly rainfall data for the period 1998 to 2012. The NDVI time series were temporally aggregated to monthly data and used as a proxy of green vegetation cover. Combined analysis of both data sources was performed to spatially evaluate the normal seasonal and inter-annual variability of soil erosion risk. This timing of erosion was compared to field evidence obtained from literature for a single location in Eritrea, and six locations in Ethiopia. Integration with other erosion-controlling factors (slope and soil erodibility) was achieved by application of the Universal Soil Loss Equation (USLE), using the FAO soil map of the world and the 90-m SRTM DEM. The USLE was applied on monthly basis, and from that aggregated to annual soil erosion. For most of Eritrea, July and August were identified as the months with highest erosion risk. Moist high lands, and arid highlands showed high potential soil erosion. Parts of the moist low lands and arid low lands have moderate risk. The soil erosion potential is low for the majority of the arid-low lands and coastal areas of the country.

Seasonal and inter-annual soil erosion assessment is used to confirm areas that have similar in climatic regime and vegetation development, which assisted to determine whether the high erosion period is always at the same moment.

This research did not intend to estimate precisely the amount of soil loss and sediment yield but to provide realistic spatial patterns of soil erosion risk, and an understanding of the temporal variability of soil erosion. This can assist decision makers developing soil and water conservation plans for the country and carry out more detailed analysis for the high potential erosion risk areas.

ACKNOWLEDGEMENTS

I would like to express my deep appreciation to the ITC, University of Twente for admitting me to pursue MSc Degree and to the Joint Japan World Bank Graduate Scholarship Programme (JJ/WBGS) who granted me the scholarship to continue my study in the highly privileged ITC University.

I would not have been accomplished my research without abundant insights and willingness to share their knowledge and support of my supervisors.

I am very much indebted and grateful to Dr. Ir. A. Vrieling, my first supervisor, for his continuous encouragement, invaluable suggestions, technical support and thoughts from the very beginning till the completion of this research. His continuous guidance and constructive feedback this research came to fruition. His door was always open and well-coming me at any time I went there. I appreciate his patience in correcting my draft thesis. His encouraging behaviour and guidance is unforgettable. During my research time I knew more valuable theoretical and practical skills than during my course study it is because of my supervisor's great willingness to share his knowledge without hesitation.

I would like to express my sincere gratitude to my second supervisor, Dr. Ir. C.A.J.M. de Bie for his supervision and feedback as well as providing me different materials which was really appreciative from the proposal writing to the final submission of my thesis.

I would like to acknowledge Dr. Michael Weir NRM course coordinator for his invaluable guidance and support during my MSc study and thesis work.

I would like to thanks to Prof. Andrew Skidmore my chairman for his constructive and valuable remarks during my proposal defence and mid-term examination.

Last but not least, I would like to say thank you to my friend Micael Gebru for his continuous encouragement from the very beginning of my study up to the end of my thesis.

I am very much grateful to all my family members for their continuous encouragement, and providing me hope. Especially to my father his continuous praying kept me healthy and happy.

Habtom T.
February, 2013
Enschede, the Netherlands.

Dedicated To The Almighty God Jesus Christ!!!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

ASTER ....Advanced space borne Thermal Emission and Reflection Radiometer
AVHRR..........Advanced Very High Resolution Radiometer
CORINE........Coordination of Information on the Environment
CDE................Centre for Development and Environment
GIS.................Geographic information system
GSFC..............Goddard Space Flight Centre
JAXA............. Japan Aerospace Exploration Agency
KE...................Kinetic Energy
MOA...............Ministry of Agriculture
NASA.............National Astronauts Space Agency
NASD.............National Space Development Agency
NDVI.............Normalized Difference Vegetation Index
RUSLE...........Revised Universal Soil Loss Equation
PR ....Precipitation Radar
SCRP..............Soil Conservation Research Programme
SPOT..............Systeme Pour l'observation dela Terre
SRTM DEM...Shuttle Radar Topography Mission Digital Elevation Model
TDRSS...........Tracking and Data Relay Satellite System
TMI................Tropical Microwave imager
TRMM...........Tropical Rainfall Measurement Mission
TMPA............Multi-satellite Precipitation Analysis
USLE.............Universal Soil Loss Equation
VIRS..............Visible Infrared Scanner

1. INTRODUCTION

1.1. Background

Soil erosion by water is the process of detachment and transport of soil by raindrop impacts and run-off. Soil erosion by water is a major problem throughout the world that has led to land degradation and adversely has affected the quality life of millions of people (Morgan, 2005). It can reduce the soil fertility and productivity through removal of the fertile top soil which is especially a problem in areas with shallow soils (Kheir et al., 2006; Mutekanga et al., 2010; Zhang et al., 2012). Furthermore, soil erosion can generate negative downstream impacts for land productivity (Vrieling, 2006), sedimentation of soil material in reservoirs, deterioration of water quality or damage to infrastructural facilities like houses, roads and canals (Morgan, 2005).

The amount of soil erosion is mainly affected by vegetation cover, topographic features, climatic variables, soil characteristics, and land use practices. Thus soil erosion is the abnormal changes of the different erosion factors (Wang et al., 2009). Most erosion occurs when high rainfall intensities coincide with limited vegetation cover (Vrieling et al., 2010). For areas with low vegetation density, rugged topography and poor land management practices, soil erosion is a primary concern as it deteriorates agricultural production and water quality (Salako, 2006; Vemu & Pinnamaneni, 2011). Therefore it may result in high economical and environmental losses in many countries (Butt et al., 2010). A total of 1,094 Million hectare land area is affected by soil erosion worldwide (Zachar, 1982). For example the exploitative land use practices due to an increasing demand for food, fiber and fodder by the growing of human and livestock populations are resposible in aggravating soil erosion in the Horn of Africa (Shiferaw, 2011). Soil erosion thus is a serious problem and will remain persistent, especially in developing countries (Morgan, 2005).

Arid and semi-arid regions are susceptible to high levels of erosion (Bouaziz et al., 2011). These areas are considered fragile environments where vegetation cover is scarce and soil erosion processes occur rapidly during rainfall effects (Vrieling et al., 2010). Sever soil erosion is one of the factors that negatively affects sustainable agricultural production in the East African highlands (Vrieling et al., 2006). For example, the Eritrean and Ethiopian highlands are severely affected, which jeoparadizes food security in these areas (Nyssen et al., 2004; Tesfahunegn et al., 2012).

The majority of Eritrea has semi-arid climatic conditions: intense rain storms and resulting runoff have a strong negative effect on the productivity of agricultural land (Nyssen et al., 2004; Tesfai & Sterk, 2002). Soil erosion, nutrient depletion and deforestation are the major environmental problems in leveling off agricultural growth in the country (Tesfamicael, 2005). Reported rates of soil loss in the Eritrian-Ethiopian highlands are very high with an estimated average of 20 tonnes $ha^{-1}year^{-1}$ and measured amounts of more than 300 tonnes ha^{-1} $year^{-1}$ on specific plots (Kaltenrieder, 2007). The Eritrean high lands (covering 19% of Eritrea) and upon which more than 65% of Eritrea's rural population depends for its livelihood is mainly mountainous, characterized by steep slopes. With the torrential nature of the rain and limited vegetation cover soil erosion has been a serious issue in this region (Semere, 2002; Tesfamicael, 2005). Besides steep slopes, and low vegetation cover combined with improper current land management practices resulted continuous deterioration of land productivity (Tesfamicael, 2005).

1.2. Soil loss estimation using remote sensing

Soil conservation planning requires estimation of soil erosion at watershed or district/regional scale. Evaluating the rate of soil erosion is essential for the development of adequate erosion prevention measures for sustainable management of land and water resources. Therefore several soil erosion predictive models and methods have been developed to assess or/and predict erosion in qualitative or quantitative approaches, such as the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978), its successor the Revised Universal Soil Loss Equation (RUSLE) (Renard & Freimund, 1994), and the Soil Erosion Risk Assessment Model (Morgan et al., 1984). These are useful tools to generate quantitative estimates important for designing conservation measures. However, performance of these models outside the region where they were developed has generally been poor (Vrieling et al., 2006) and collecting input data for the different models have being a major obstacle for estimation of soil loss in an area (Bouaziz et al., 2011). Satellite remote sensing provides an alternative for gathering model input data at a larger scale.

Satellite remote sensing can provide useful input data for the qualitative mapping of potential soil erosion and soil erosion risk for the regional or continental scale (Vrieling, 2006). It also has a high potential for the collection of soil erosion data due to the large spatial coverage, the regular time interval between acquisitions, provides both spatial and temporal with different resolutions for soil erosion assessments (Dejong, 1994). Therefore the required input data obtained from satellite remote sensing has partly replaced the tedious work of field surveying (Lal, 2003). Remote sensing data and derived information has frequently been used in erosion models to predict soil erosion. Satellite-derived soil erosion risk maps display areas likely to face erosion hazards. For example Coordination of Information on the Environment (CORINE) contained a qualitative erosion risk mapping model to assess soil erosion risk in Europe based on slope, soil, rainfall and land cover (Nigel & Rughooputh, 2010). Some higher resolution satellites like ASTER, IKONOS and Quick Bird can directly detect eroded features (individual large erosion features, discrimination of eroded areas) or detect erosion consequences (Vrieling, 2006; Vrieling et al., 2008). Alternatively, satellite data can allow for the assessment of erosion controlling factors like vegetation, rainfall erosivity and topography (Vrieling et al., 2008). Prior remote sensing satellite development, aerial photo interpretation both for detecting erosion features and obtaining model input data has been used for soil erosion research. Hence remote sensing and GIS applications combined with erosion models are an adequate method to evaluate erosion hazards (Kefi et al., 2011). However for satellite applications and models to obtain realistic results, a detailed assessment of the different erosion factors is necessary.

Vegetation cover is one of the main erosion factors that can be estimated through remote sensing satellites, for example through the use of vegetation indices. Several vegetation indices exist that combine spectral bands to generate an indication of the vegetation cover. The Normalized Difference Vegetation Index (NDVI) is the most used vegetation index. Vegetation indices allow us to map the distribution of green vegetation based on the characteristic reflectance patterns (the most common characteristic used is high reflection in near-infrared and low in red). The NDVI is strongly related to photosynthetic activity of healthy green leaves which strongly reflect near-infrared radiation, and absorb red radiation through leaf chlorophyll and other pigments. The NDVI is calculated as follows:

$$NDVI = (NIR - red) / (NIR + red) \quad \text{Equation (1)}$$

NDVI ranges between -1.0 and 1.0. Higher NDVI imply a more healthy green vegetation cover. NDVI values of zero and near to zero are bare grounds and negative values are water bodies.

At any location soil erosion shows strong temporal variation (Vrieling et al., 2008). Both rainfall erosivity and land cover are the most dynamic in nature and having predominant importance among soil erosion factors (Angulo-Martinez & Begueria, 2009; Vrieling et al., 2010). Thus understanding the relationship between rainfall and vegetation dynamics is important for erosion assessments. Temporal variability mainly deals with the timing of erosion related to periods of high rainfall intensity and to seasonal changes in vegetation cover. Higher erosion rates generally occur at the beginning of the wet season when rainfalls coincides on the ground when vegetation cover is limited (Symeonakis & Drake, 2010). "According to the study conducted based on USLE from the data base of Soil Conservation Research Programme (SCRP) of Eritrean and Ethiopian highlands; areas that have a low (0-30%) to moderate (30-60%) vegetation cover all storms can cause erosion and high erosivity periods (> 30 MJmm/hahyr) cause about 20% of the soil loss, low and moderate erosivity periods (5 – 20 MJmm/hahyr) cause about 40% of the soil loss recorded. Even, under maximum plant cover (> 60%) only periods with erosivities higher than 500 MJ mm/hahyr caused a few high soil losses" (Kaltenrieder, 2007).

Estimating of rainfall erosivity with vegetation cover conditions may provide effective temporal erosion rate characteristics for the study area. Moreover, assessment of potential soil erosion risk maps is possible using input variables derived from soil maps, multi-temporal satellite imagery, slope data and limited amount of ground data (Van der Knijff, 2000). This way, erosion risk can be assessed over large areas, spatially diverse areas without the need for extensive field surveys.

1.3. Factors affecting soil erosion

There are several factors influencing the rate of soil erosion that controls soil loss and spatial characteristics in an area. The main factors that influence erosion are rainfall intensity which gives (erosivity), vegetation cover, topography and soil properties (erodibility) and conservation practices (Morgan, 2005).

Rainfall erosivity: "Rainfall erosivity is the aggressiveness of the rain to cause soil erosion" (Morgan, 2005). It's the most important climatic factor, which can directly influence erosion. Amount and frequency as well as drop size are other effective parameters of rainfall to cause soil erosion (Lal, 2003). Rainfall erosivity is a measure for the erosive force of rainfall, or stated differently the ability or power of rain to cause soil erosion. It determined by the kinetic energy of rainfall which also depends on rainfall intensity. Therefore erosivity is a function of the physical rainfall intensity that includes rain depth, drop size distribution and terminal fall velocity (J. Nyssen et al., 2005). To assess the erosivity of a rainstorm, one has first to determine the energy of the rainstorm using certain formulas that have been developed to calculate the energy of the rainstorm on the basis of obtained rainfall intensity data.

Soil erodibility: is the resistance characteristic of a soil to detachment and transportation by erosion agents. This is a function of particle size distribution, organic matter, soil structure permeability and pore stability. In terms of soil properties; silt, very fine sand, and clay soils tend to be less erodible than sand, sandy loam, and loamy soils also existence of stones over the soil surface may reduce erosion by protecting soil from rain splash (Yuksel et al., 2008).

Topography: slope has high influence in soil erosion. Steep slope areas have crucial effect on amount of soil loss. Moreover steep slopes are susceptible for erosion hazards especially if human activities like land clearance, overgrazing, expansion of crop land to marginal and poor soil management practices are added to that it becomes very severe erosion. In areas that have steep and long slope length may have higher soil loss than in areas that have less steep and short slope length.

Vegetation cover: "vegetation cover is one of the most crucial factors in reducing soil erosion" (Yuksel et al., 2008). Vegetation protection reduces rainfall impact, soil detachment and runoff transport capacity. It can be described as a green vegetation cover as well as non-photosynthetic ground cover elements. In general vegetation reduces soil erosion by protecting the soil against the action of falling raindrops, increasing the degree of infiltration of water into the soil, reducing the speed of the surface runoff, binding the soil mechanically, maintaining the roughness of the soil surface (de Asis & Omasa, 2007). The vegetation cover is an erosion-controlling factor that is most affected by human interference. Therefore, it is an important component of any predictive soil erosion model (Bouaziz et al., 2011). Vegetation cover is one of the most dynamic seasonal variables that control erosion. Vegetation cover varies throughout the year in time and space.

Areas with low vegetation density, rugged topography and poor land management practices soil erosion is a primary concern in deteriorating agricultural production and water quality (Salako, 2006; Vemu & Pinnamaneni, 2011). Moreover, there are several triggering factors such as economical, social, political and policy factors which aggravated the rate of soil erosion in many areas related to an increasing demand for food, fibre and fodder due to growing human and livestock populations are responsible (Morgan, 2005; Shiferaw, 2011). Vast areas of land now being cultivated may be rendered economically unproductive if the erosion of soil continues (Salako, 2006).

1.4. Universal soil loss equation (USLE)

Universal soil loss equation is an empirical model used to measure soil loss quantitatively from a specified fields which developed by Wischmeier and Smith (1978). It is one of the common widely applied soil erosion model. It is an erosion model used to determine long-term average soil losses on a specific plot. USLE is used to estimate the potential soil erosion of an area which can be expressed by the formula below:

$$A = R \times K \times L \times S \times C \times P \qquad \text{Equation (2)}$$

Where, A is the mean soil loss tonnes per hectare per year. And R is average rainfall erosivity factor. R-factor is one of the main erosion indexes measuring the force of specific rainfall. The unit of erosivity is $Jm^{-1}h^{-1}$. K is soil erodibility factor; it is the soil loss rate per erosion index having a unit of ($tmhha^{-1}J^{-1}$). The range stretches from 0 up to 1. LS are slope length and slope steepness factors used to assess severity of soil erosion by computing the effect of slope steepness and length. C-factor is cover factor used to reflect the effect of cropping and management practices on erosion rates which represent the effects of plants, soil cover, soil biomass, and soil disturbing activities on erosion. The C-factor data can be collected from ground or derived from vegetation cover (Symeonakis & Drake, 2010). The C- factor is dimensionless and has values between 0 and 1. The P-factor is the support practice factor is defined as the ratio of soil loss with a specific support practice to the corresponding soil loss with up-and-down-slope cultivation. The P Factor is reflecting the impact of supporting practices on the erosion rate. It is dimensionless and has values between 0 and 1.

USLE model is especially useful for construction sites and non-agricultural areas. However it has some draw backs it does not predict deposition and compute sediment yields (Wischmeier & Smith, 1978). Another limitation is that it's not an event based model hence it cannot identify causing large scale soil erosion in one rainfall. To overcome this limitation some improvements has been done to the model as Revised Universal Soil Loss Equations (RUSLE) to improve some of the factors such as for rainfall erosivity factor, crop management factor and soil erodibility factor (Renard & Freimund, 1994).

1.5. Problem Statement

For this study the list of problems are expressed as:

- Although Eritrea is heavely affected by soil erosion, still there is little to no spatial and temporal information at national scale as to where and when erosion is occuring.
- Current erosion mapping efforts hardly accounts for the strong seasonal variability of erosivity and vegetation cover: yet the combined effects of these factors strongly determines if and when erosion takes place.
- Some years intense erosion occurs, other years hardly, depending on rainfall characteristics during the year. Little spatial information exists about such inter-annual variability.

1.6. Research objective

The main objective of this study is to estimate spatial and temporal patterns of soil erosion for Eritrea. For that purpose, temporal and spatial variability of rainfall erosivity and green vegetation cover is studied and integrated through a model using TRMM rainfall intensity estimates and 10-daily SPOT VGT-NDVI images (1998 -2012) respectively. This objective is decomposed in to the following specific sub-objectives.

- to estimate rainfall erosivity over Eritrea based on a 3-hourly TRMM rainfall product (1998-2012).
- to gather existing ground data and review literature for Eritrea regarding the timing of erosion.
- to evaluate the normal seasonal and inter-annual variability of rainfall erosivity over Eritrea based on 3-hourly TRMM precipitation data (1998-2012).
- to assess the normal seasonal and inter-annual variability of green vegetation cover for Eritrea using 10-daily SPOT VEGETATION NDVI time series (1998-2012).
- to identify when and where during a normal year erosion risk is highest, based on a combined analysis of erosivity and vegetation cover.
- to demonstrate the importance of inter-annual variability on erosion risk in Eritrea from the satellite-based analysis.
- to estimate whether the spatial and temporal (seasonal and inter-annual) patterns of erosion and rainfall erosivity derived from satellite data correspond to existing ground data.

1.7. Study design

The study was carried out without any fieldwork. Therefore, most data were obtained from satellites. Ground evidence data were obtained from literature through contacting responsible organizations and researchers. Based on these input data can be divided in to three classes. Ground evidence data, gathered remote sensing soil erosion factors and two additional data. All these input data used to assess the potential soil erosion risk in space and time. The two multi-temporal remote sensing satellite products used are; 3-hourly TRMM-3B42 rainfall intensity and SPOT-VGT-NDVI 10 day's synthesis products. Rainfall erosivity and vegetation cover variability were assessed seasonally and inter-annually on monthly basis in a time series (1998-2012). These two input data were combined to estimate the potential soil erosion risk for the study area also. Besides to the satellite analysis; temporal ground evidence rainfall erosivity data and soil loss obtained from literatures which cover six soil erosion research stations provided a partial validation for soil erosion severity in the study area. The two additional input data were STRM DEM to derive a slope map and the FAO soil map of the world to derive a soil erodibility map. Finally for better spatial and temporal soil erosion representation potential soil erosion risk was assessed using USLE approaches.

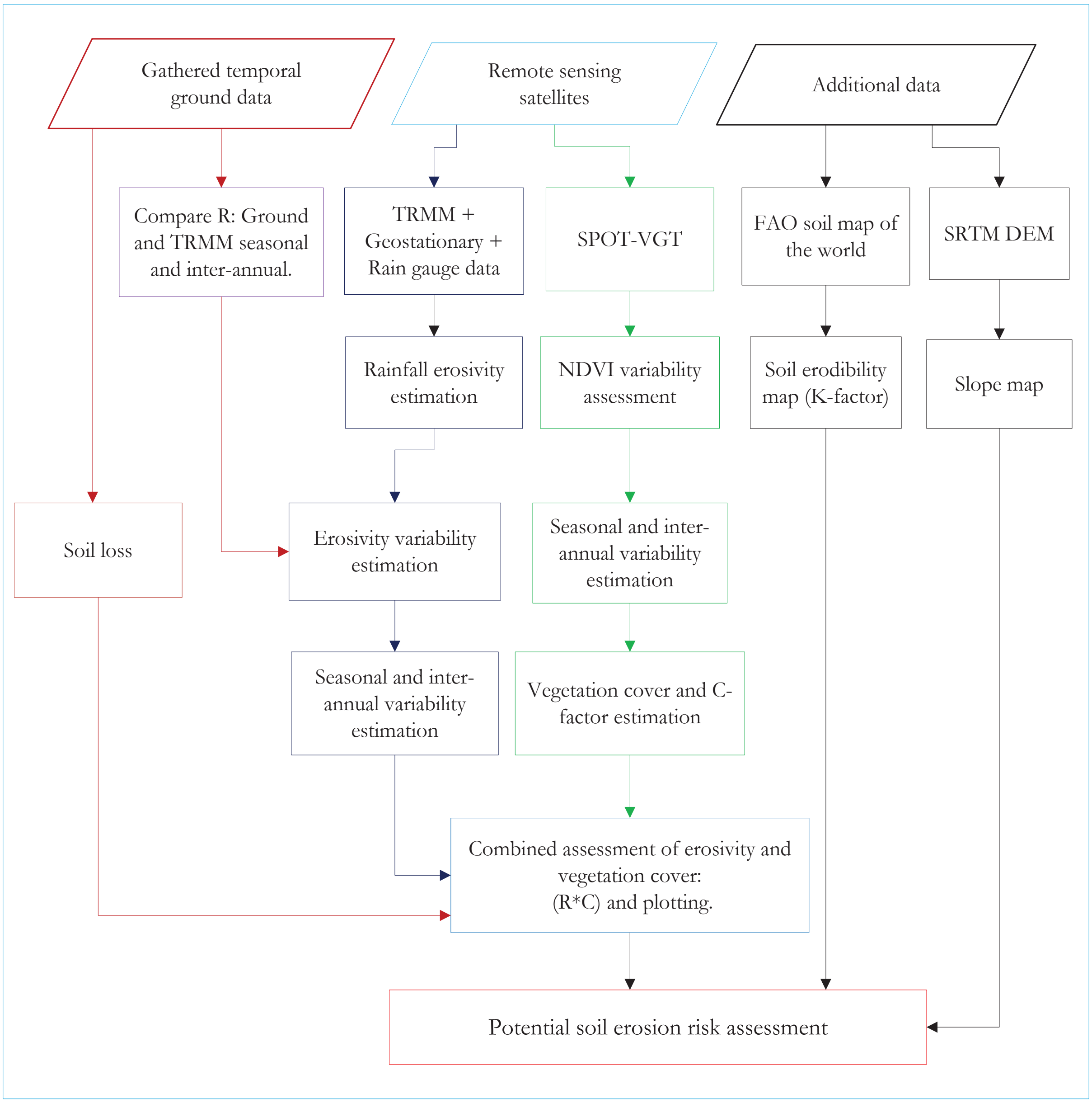


Figure 1: Study design

2. STUDY AREA

2.1. Location of Eritrea

The study area (Eritrea) is located in East Africa. It is bordered by Sudan to the west, to the south Ethiopia, to the south- east Djibouti and to the east Red Sea. Eritrea has a total land area of approximately 124,320 km^2. There are six administratvie zones and 54 sub-zones /districts in the country.

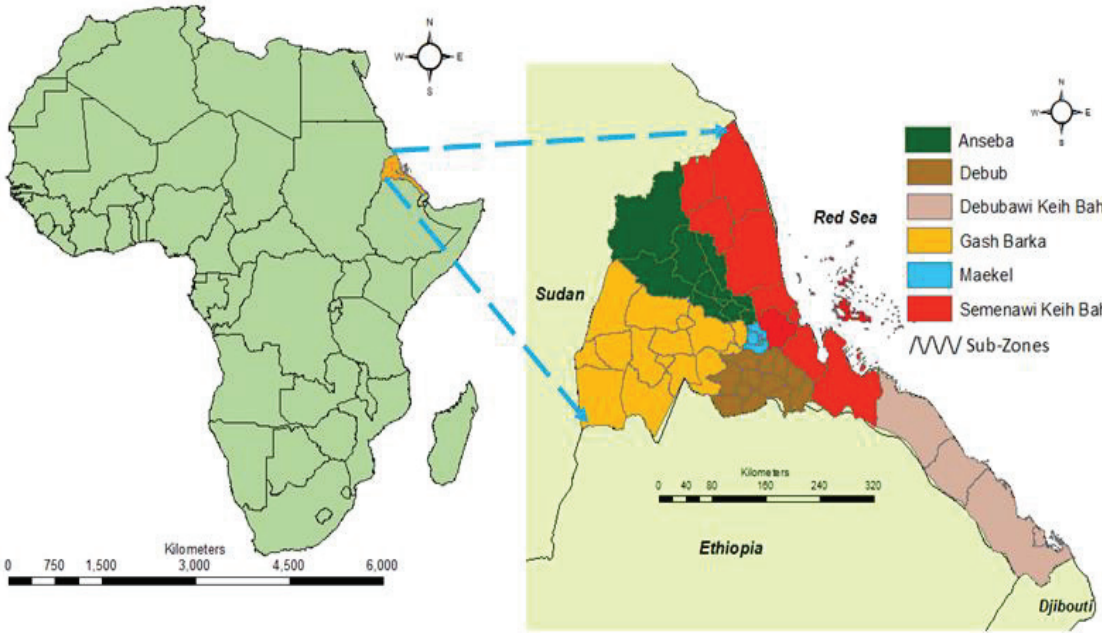


Figure 2: The location of Eritrea in Africa, and its administrative zones and sub-zones

2.2. Agro-ecology

The climate of Eritrea is dominant semi-arid with arid coastal areas to temperate in the highlands and isolated sub-humid micro-catchments of the eastern escarpements. Therefore based on climate, soil types and other parameters, Eritrea is divided into six agro-ecological zones: moist highlands, arid highlands, sub-humid highlands, moist lowlands, arid lowlands and semi-desert (Figure 3). The rainfall regimes are strongly influenced, by topography. The average annual temperature ranges from 16 C^o in the highlands to 30 C^o in the low lands. Altitudes range from 60 metres below sea level to 3100 metres above sea level (Ogbazghi et al., 2011). This complex series of landscape and climatic features is characterized by vertical zoning, which go from semi-desert to high-mountain environments. Eritrea contains a diversity of land uses, with main land use activities being agriculture and pastoralism. "Approximately 70% of Eritreans depend on agricultural activities largely on crop cultivation and livestock rearing and fishing for income and food" (MOA, 2002; Tesfamicael, 2005). The fact that agriculture is the most important sector of the country's economy and accounts for most exports and Gross Domestic Product (GDP) explains why the demand for arable land and land for grazing, forestry, wildlife, tourism and urban development is increasing.

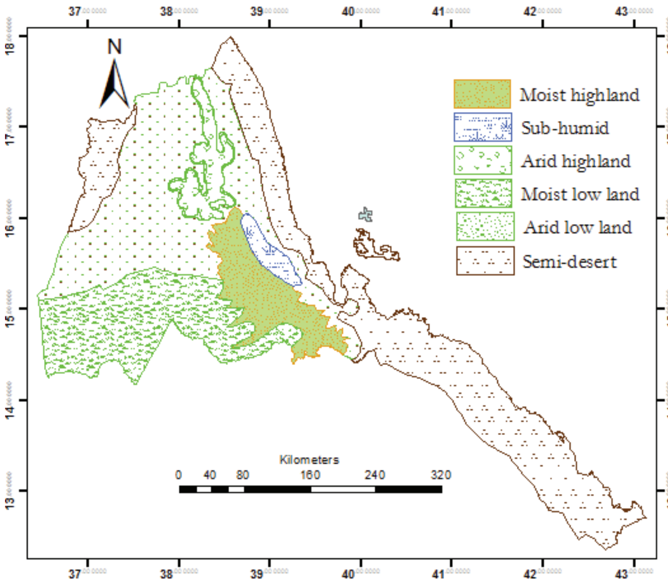


Figure 3: Agro-ecological zones of Eritrea (Ogbazghi et al., 2011).

Figure 4 shows a map of average annual rain fall for Eritrea, generated from from TRMM-3B43 version-7 monthly products . For each pixle and year, all monthly values were summed, and then all annual rainfall values were averaged for each pixel. The total average annual rainfall increases from 200 mm in the north and coastal areas to more than 700 mm in the south and western lowlands. Comparision with figure 3 indicates that arid-low lands and semi-desert agro-ecological zones receive significantly lower precipitation than moist low lands and moist highlands agro-ecological zones.

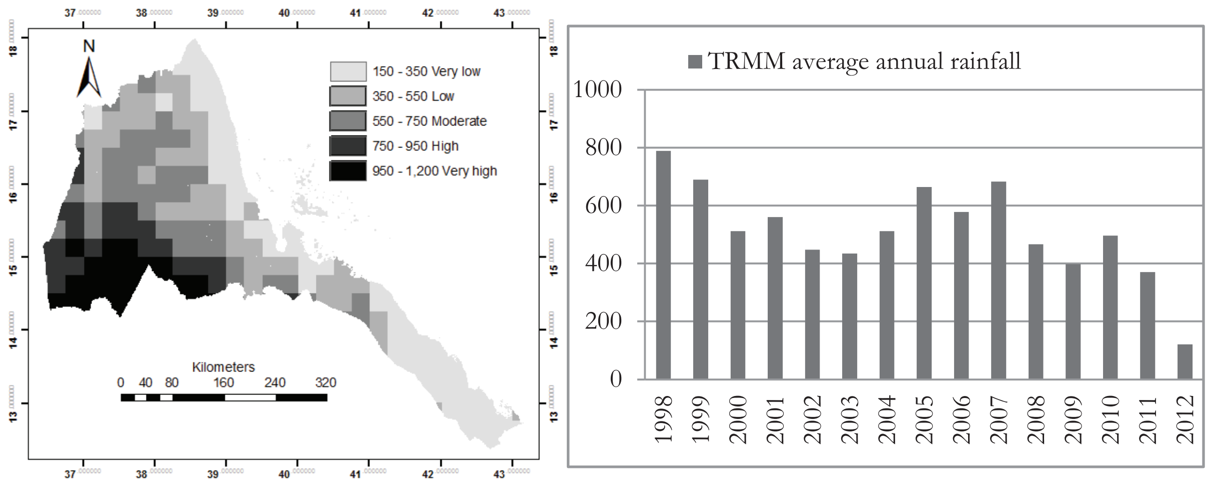


Figure 4: TRMM -3B43-V7 Average annual rainfall (mm) distribution (1998 up to 2012).

The study area has varied elevations. It ranges from 100 metres below sea level up to 3100 metres above sea level. The country is dominated by rugged topography especially arid high lands, sub-humid, moist high lands and some parts of arid low lands agro-ecological zones. The nature of the topography of the country makes very sensitive for soil erosion. Figure 5 shows the slope gradient derived from the Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) of Eritrea. The slope gradient was calculated in Arc GIS and subsequently re-sampled to 1-km resolution for comparison with other data layers in this study.

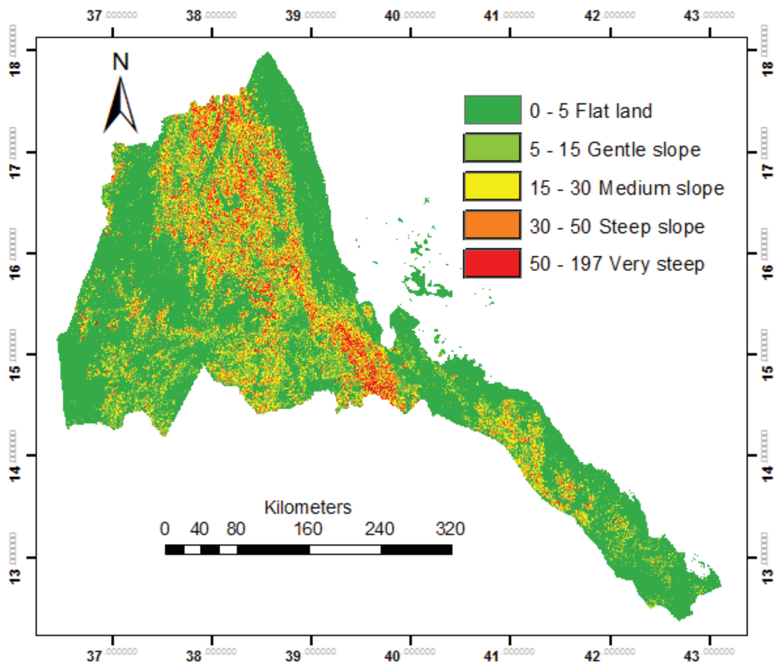


Figure 5: Slope map for Eritrea derived from the SRTM-DEM (in percentage)

2.3. Soil erosion in Eritrea

The increase of land conversions to maximize crop production for the market and domestic satisfaction, both the process of concentration on existing arable land (over cultivation) and the pressure to exploit marginal lands have intensified soil erosion (Ogbazghi et al., 2011). In 1998, the area under cultivation expanded by 10% (approximately almost 44 thousand ha) compared to 1993 (MOA, 2002). The country's forest cover has declined dramatically from 30% of the total land area at the beginning of 1900 to less than 1% at present (Boerma, 2006). Areas that used to have dense vegetation already lost their stand of trees. This especially holds the high lands of Eritrea which was once probably covered with evergreen montane forest is now intensively used for cultivation (Semere, 2002). Today, only scattered remnants of this montane forest remain. Such land management practices leaves soils bare and exposed, increased their vulnerability to the high erosive rain.

Uncontrolled grazing, growing demands for fire wood or charcoal and cultivation expansion are often the main cause for deforestation (MOA, 2002; Ogbazghi et al., 2011). Due to the reduction of protective vegetation cover in large parts of Eritrea, the soils are highly exposed to massive erosion. Many soils are no longer able to support the crop production as they have lost their fertility and are very shallow which reduces their water retention capacity (Semere, 2002). Soil erosion is a serious problem throughout Eritrea, even if quantitative estimates of its extent and intensity are lacking. Estimations of yield decline due to soil erosion, annual yield losses for Eritrea are estimated in the range of 0.3 and 0.6% year^{-1} (MOA, 2002; Tesfamicael, 2005). Furthermore an estimated 2.4 million ha of the central highlands region (including especially its northern portion) had by 1984 been degraded and the soil loss from sheet and rill erosion in this region is in the range of 5-100 t/ ha^{-1}year^{-1} (MOA, 2002).

Despite erosion being an important process in Eritrea few field studies have been performed in Eritrea on soil erosion. Most of them were performed at the watershed scale and for small areas. The best example is the erosion research programme that has been carried out by the Centre for Development and Environment in Afdeyu. Afdeyu village is one of the six Soil Conservation Research Programme (SCRP) research sites located in the central highlands of Eritrea about 22 km north of Asmara. The site lies at an altitude ranging from 2310 to 2460 meters above sea level. This soil erosion research centre is 263 ha which is used to assess soil erosion quantitatively since 1984 (Stillhardt et al., 2002). Similar five SCRP research sites (May bar, Hunde lafto, Gununo, Anjeni, and Andit tid) are located in the Ethiopian highlands. The research sites were established by Ministry of Agriculture and Swiss organization Centre for Development and Environment (CDE) University of Bern in both countries. The sites are used for soil conservation researches based at field stations having the best ground data for erosion assessments such as erosivity, runoff and soil loss in the high lands of the two countries since (1985 to 2002) (Ogbazghi et al., 2011; Stillhardt et al., 2002).

For example the mean soil loss calculated from the four test plots of Afdeyu was 40 tonnesha^{-1} (Ogbazghi et al., 2011; Stillhardt et al., 2002). Similar studies done in Afdeyu mean soil loss estimated was 15-35 tons ha^{-1} of soil are eroded annually (MOA, 2002; Negassi et al., 2000). Herweg and Stillhardt (1999) estimated the mean soil loss in Afdeyu to be 17-20 tons ha^{-1}yr^{-1}. The amount of soil loss obtained from different test plots varied yearly depending on the amount of rainfall erosivity and cultivation practices.

2.4. Soil and water conservation practices in Eritrea

Large scale soil and water conservation programmes and reforestation activities to address problems of land degradation were initiated at the beginning of 1970 under the umbrella of the World Food Program (Food for Work) to combat sever soil degradation in the highlands (K.; Herweg & E. Ludi, 1999). These efforts tried to mobilize the whole community to participate in soil and water conservation and afforestation programmes.

Bench terraces and contour bands that were constructed in the late 1970s and 1980s are still clearly visible in many areas of the highlands (Nyssen et al., 2004). Many farmers have accepted the introduced soil and water conservation measures and have maintained them ever since. From 1971 to 1978 on 1,586 ha trees are planted to protect the areas from erosion in the highlands and in between 1979 and 1991, it is estimated that 27,000 ha were terraced and planted with tree seedlings (Negassi et al., 2000). After independence from 1992 – 1998 more than 54,229 ha soil and water conservation practices have been carried out on-farm and off-farm together with afforestation programmes on hillsides and enclosures (MOA, 2002). These campaigns involve construction of soil and water conservation terraces, both on farms and on degraded hillsides to reduce slope gradient so as to slow down the flow speed of runoff water. On hillside terraces, a variety of indigenous and exotic trees and shrubs have been planted, while on farm lands efforts are focused on trying to stabilize the physical structures by planting multipurpose grasses (animal fodder and soil protection). Local-level initiatives have also complemented these efforts, especially in the area of soil and water conservation on individual farms and the development of woodlots in homesteads and near villages and especially on sacred sites. Local knowledge and farmer's initiatives are integrated with introduced soil and water conservation techniques at various degrees. Therefore as impact assessments demonstrated; clear benefits of the soil conservation measures in controlling runoff and soil erosion has been achieved (Nyssen et al., 2004).

However, most of the practices designed to address the problem have fallen short of expectations and were not much effective. Often farmers failed to adopt the recommended interventions or abandoned them when the project ended (MOA, 2002). The main obstacle still existing is the security of land tenure. Current land has a rotation period of 5-7 years which is too short for long term investments in improving the land such as tree planting and soil and water conservation structures. Moreover the increasing number of browsing livestock without fee restriction for farmers can bread hundreds then grazing continuously in the open communal land which does not give time for vegetation regeneration (MOA, 2002; Negassi et al., 2000; Ogbazghi et al., 2011). The tenure systems in practice has not encouraged innovation, nor have they permitted new sustainable land management practices and modern ways of exploiting land to improve production and did not enhance protection or proper use of the environment (Ogbazghi et al., 2011). Besides the top-down approach did not consider farmers participation in planning process. Moreover, investment in soil conservation technology may, from the farmer's point of view, not be viable in the short term, and even though the net social benefits are positive.

This assessment of soil erosion risk mapping using satellite imagery; could assist decision makers to observe the extent and severity of erosion rates at national level. It may help to reconsider the traditional soil and water conservation measures with more sustainable and intensive practices. In addition understanding of the different erosion controlling factors is important to implement large scale soil and water conservation in particular and environmental protection in general to prevent current erosion processes in the country.

3. MATERIALS AND METHODS

3.1. Data

The main derived-satellite data sources that are used for this study are NDVI time series from SPOT VGT (Systeme Pour l'Observation de la Terre VEGETATION), and precipitation estimates obtained from the Tropical Rainfall Measurement Mission (TRMM). Additional spatial data used include; the Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) to derive slope gradient and the FAO harmonized world soil map to derive the soil erodibility factor. Temporal rainfall erosivity and soil loss based on ground data (1984-2002) were gathered from literature.

3.1.1. SPOT-VGT NDVI

The VEGETATION sensors of the SPOT -4 and -5 satellites have a 2250 km swath width and perform daily imaging for most of the earth's surface. The SPOT -4 and -5 platforms were launched in 1998 and 2002 respectively. SPOT-VGT is a multispectral instrument with four spectral bands: blue, red, near-infrared and short wave infrared. There are three types of VGT products available from the Flemish Institute for Technological research (VITO): primary products (P), extracted from a single image segment, daily (S1) or ten-day (S10) syntheses; these are mosaics of acquired image segments, respectively for 24h periods and for 10 days. Vegetation indices (NDVI) are calculated from daily or ten-day syntheses. Vegetation index products from VGT include S10 for 1 km^2 data, S10.4 for 4 km^2, and S10.8 for a resolution of 8 km^2. In this study the 1-km^2 10-daily (S10) NDVI composites were used.

3.1.2. Tropical Rainfall Measuring Mission (TRMM)

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission of the National Aeronautics and Space Administration (NASA) and Japan Aerospace Exploration Agency (JAXA, previously known as National Space Development Agency, or NASDA). It is the first coordinated international satellite mission to monitor and study rain systems tropical and subtropical areas. The TRMM satellite was launched in December, 1997 and is actively acquiring data until present.

Rainfall products from TRMM are produced in the NASA Goddard Space Flight Centre (GSFC) which provided the TRMM Microwave Imager (TMI), the Visible Infrared Scanner (VIRS), and the observatory, and operates the TRMM satellite via the Tracking and Data Relay Satellite System (TDRSS) or the Precipitation Radar (PR). The TRMM orbit is circular, non-sun-synchronous. The TRMM satellite orbits the earth at an altitude of 403 km and collects data between 50^0 north and 50^0 south. This satellite provides extensive coverage in the tropics and allows each location to be covered at different local time each day.

The Version 7 TRMM Multi-satellite Precipitation Analysis (TMPA) product consists of three products at different temporal resolutions: 3-hourly and daily (3B42) and monthly (3B43). The spatial resolution for all three products is 0.25° x 0.25° (approximately 27km). The spatial resolution of TRMM is fairly high from a global point of view, but it is low when working on small scales like watersheds. These products are not only depending on TRMM information also from geostationary infrared observations (from other satellites), and rain gauge ground data. For this study version 7, 3-hourly 3B42 and monthly 3B43 precipitation data was used.

3.1.3. Digital elevation model and soil map

The Shuttle Radar Topography Mission produced a digital elevation model of the Earth. The project was a joint endeavour of NASA, the National Geospatial-Intelligence Agency and other European countries. The satellite operated during 11 days in February 2000. The DEM obtained (http://srtm.csi.cgiar.org/) from its C-band acquisitions has a 90-metres resolution and covers the earth's surface between 60^0N and 57^0S. For this study, slope gradient was calculated from this DEM using Arc-GIS 10 analyst tools, re-sampled to 1km resolution to match the NDVI data source.

The soil map for the study area was derived from Food and Agriculture Organization (FAO) harmonized world soil map (http://www.fao.org/nr/aboutnr/nrl/en/). The FAO soil map of the world provides several parameters such as grain size distribution, clay mineralogy, soil depth, and soil and terrain suitability for specific crop production, soil moisture, storage capacity and soil drainage classes. For Eritrea it contains 12 common soil classes. Based on the soil properties for the study area the erodibility factor (K-factor) was derived for each soil unit. For this purpose, the nomograph of Wischmeier and Smith (1978) was used. Based on the K-factor values a map of soil erodibility was then constructed.

3.1.4. Evidence ground data

Temporal ground evidence data on rainfall erosivity and soil loss were collected from literature (Haile et al., 2006; Herweg & Stillhardt, 1999; Ogbazghi et al., 2011; Stillhardt et al., 2002). These studies provided data for a single location in Eritrea (Afdeyu) for the period 1984 – 2002. In addition, data for five soil erosion research centres in Ethiopia were obtained to further compare rainfall erosivity and soil loss with the results of this study. These research stations are operated with the collaboration of the University of Berne under the name soil conservation research programme (SCRP) and are assumed representative for erosion in the highlands of Eritrea and Ethiopia. To check whether newer data for the same stations exists and whether data for other stations existed Anton Vrieling (my supervisor) contacted Thomas Kohler from the University of Berne (Switzerland) which is the host for the research stations and Dr.Woldesselassie Ogbazghi from the Hamelmalo college of Agriculture (Eritrea). However, this did not result in further data that could be used in this study.

The ground data in Afdeyu were collected from test plots for assessing severity of rainfall erosivity and soil loss for the SCRP research sites and are given in (Haile et al., 2006; Herweg & Stillhardt, 1999; Ogbazghi et al., 2011; Stillhardt et al., 2002). The soil loss data gathered from test plots of the six SCRP sites have different slope gradients, different land use practices and different management practices. For soil loss estimation in the plots different soil and water conservation practices are established to evaluate the efficiency of each. Moreover, the type of soil for erosion susceptibility (soil erodibility) K-factor was taking in considerations for erosion evaluations. The data contains erosivity and soil loss for individual years, averaged over the plots contained in each research site. In addition, multi-year average monthly erosivity and soil was provided. For most sites the period 1985-2002 is covered by the reported data with some missing data during 1992 and 1993. These obtained ground data served as a means of partial validation for the temporal rainfall erosivity derived from TRMM-3B42, and of soil erosion derived from TRMM and SPOT VGT.

3.2. Methods

3.2.1. Rainfall erosivity estimation from TRMM

The Universal Soil Loss Equation (USLE) is an erosion model designed to predict average soil losses from runoff from specific field areas in specified cropping and management systems (Wischmeier & Smith, 1978). The USLE calculates long-term average soil loss by multiplying the six erosion factors that include rainfall, soil erodibility, slope gradient and length, vegetation cover, and management practices. When factors other than rainfall are held constant, storm soil losses from cultivated fields are directly proportional to a rainstorm parameter identified as the EI (Erosion Index) (Wischmeier & Smith, 1978).

To assess the rainfall erosivity of a rainstorm, determining the energy of the rainstorm is crucial. A number of formulas have been developed to calculate the kinetic energy of the rainstorm on the basis of its intensity. Knowledge of the relationship between rainfall intensity and kinetic energy and its variations in time and space is important for erosion prediction (Van Dijk et al., 2002). Since the energy of a given mass in motion is proportional to velocity-squared, rainfall energy is directly related to rain intensity. The most widely used kinetic energy-intensity relationship is that developed by Wischmeier and Smith (1978). This relationship can be expressed as:

$$\mathrm{KE} = 916 + 331 \log_{10} \mathrm{I} \qquad \text{Equation (3)}$$

where, KE is kinetic energy expressed in foot-tones acre^{-1} intensity (I) in inchesh^{-1};

Following a review of existing relationships between kinetic energy and intensity, Van Dijk et al. (2002) developed an equation that better fitted the different global datasets, i.e.

$$\mathrm{KE} = 28.3[1 - 0.52 \exp(-0.042\mathrm{I})] \qquad \text{Equation (4)}$$

where KE is expressed in MJ ha^{-1} and intensity (I) in mmh^{-1}

For this thesis this equation was applied. The constants of the equation were chosen as an available estimate without having local measurements of rainfall kinetic energy and it can serve for both areas of higher rainfall areas and low rainfall experiencing areas (Mikos et al., 2006). Research findings suggest that the relative accuracy of storm kinetic energy prediction is greatest for storms (Van Dijk et al., 2002). Moreover, there is no site specific equation for the relationship between kinetic energy and rainfall intensity which is specific for Eritrea.

The sum of the kinetic energy values for all time periods during a storm results in the total kinetic energy of that storm. In order to determine the erosivity of each rainfall storm, the total energy of the storm (E) is normally multiplied by the I_{30} of the storm, following Wischmeier and Smith (1978). The parameter I_{30} reflects the maximum intensity during any 30 consecutive minutes of the storm.

EI_{30} = total storm energy × maximum 30-min intensity Equation (5)

EI_{30} is not simply an energy parameter. Rainfall energy alone is not a good indicator of erosive potential due to the increase of raindrop erosion and runoff with intensity. EI_{30} reflects how total energy and peak intensity are combined in each storm and how particle detachment is combined with transport capacity.

The R-factor is used in the USLE as the measure for erosivity, i.e. the erosive force of the rainfall. For that all EI_{30} were added for all storms in a year. The average annual erosivity can then be obtained as an average of all yearly R-factors. In this study, the R-factor was derived from rainfall intensity collected from the 3-hourly TRMM 3B42 rainfall intensity products following the approach of Vrieling et al. (2010). For each 3-hourly period and each TRMM pixel the kinetic energy was estimated following equation 4. The 3-hourly rainfall intensity values are used as an input (i.e. the I in the equation). Subsequently, for each 3-hourly period this estimated kinetic energy was multiplied by the intensity, as in equation 5. Because we lack information about the distribution of rainfall intensities within the 3-hourly periods, the I_{30} was considered to be equal to the intensity reported in the TRMM dataset. This will likely cause an underestimation of erosivity. This gives the following equation for the derived total kinetic energy per 3-hours (E_{3h}) for each 3-hour period (rainfall during 3 hours = 3I):

$$\mathrm{E3h} = \mathrm{KE} \times 3\mathrm{I} \qquad \text{Equation (6)}$$

where, E_{3h} is in MJ ha^{-1} and 3I is the rain (mm) in 3hours. The annual erosivity (R) is then calculated as follows:

$$\mathrm{R} = \sum_{k=1}^{n} (\mathrm{E3h})\mathrm{k} \times (\mathrm{I30})\mathrm{k} \qquad \text{Equation (7)}$$

where, R is the R-factor for a specific year expressed in MJ mm ha^{-1} h^{-1} $year^{-1}$, N is the total number of 3-hourly periods in a year, and I_{30} is the maximum 30-min rainfall intensity in mm h^{-1}. Similarly we also obtained erosivity values for each month and TRMM pixel by providing a summation of the EI_{30} on a monthly basis (so taking N as the number of 3-hourly periods in a specific month). The unit for these monthly erosivity values is MJ mm ha^{-1} h^{-1} $month^{-1}$.

3.2.2. Seasonal and inter-annual variability of rainfall erosivity

The analysis was conducted based on the monthly and annual rainfall erosivity estimates that we are derived from the TRMM 3B42 dataset section 3.2.1). For effective summary of the variability of erosivity in Eritrea, spatial maps of erosivity were constructed that show the erosivity in specific months, and years. In addition, maps were produced that show multi-annual (1998-2012) averages of monthly and annual erosivity. In this case, for example, the June erosivity maps of all years were averaged to obtain the June erosivity of an average "representative" year.

The normal seasonal changes in rainfall erosivity of wet and dry seasons were estimated through averaging results of the same months, but different years. This assessment was conducted on monthly basis to observe the spread and variability of erosivity during an average "representative" year.
To observe the variability and relationship between rainfall and rainfall erosivity all pixels values were compared using a scatter plots.

Findings of the temporal analyses of erosivity were compared with the erosivity observations at the six SCRP ground stations. For that purpose, time series for the six TRMM pixels were selected that covered each of the sites. The comparison between TRMM and ground- based erosivity consisted of (1) an evaluation whether the average seasonal behaviour was similar in both datasets, and (2) an evaluation of whether TRMM captured a similar inter-annual variability of erosivity. In addition, the mean of all months erosivity ground data of Afdeyu were also compared with average monthly TRMM derived erosivity data (1998-2002) then R^2 regression was produced to observe the correlation between them. Therefore, this ground data and satellite TRMM data displayed severity of erosivity in SCRP research sites. From the six stations; Afdeyu received the lowest rainfall and have the lowest erosivity measured in the SCRP sites both in ground and TRMM products but the potential soil loss is high due to limited vegetation cover.

3.2.3. Seasonal and inter-annual variability of green vegetation cover

NDVI is directly derived from spectral observations by satellites. The quality of NDVI maps thus strongly depends on: the quality of the original images (dependent on cloud cover) and pre-processing performed on the original NDVI images. Particularly during the humid period, cloud cover can result in poor NDVI observations.

To reduce this effect temporal filtering of the NDVI was done using an iterative Savitzky-Golay filter (Chen et al., 2004). For each pixel each value in the time series was replaced with a new value which is obtained from a polynomial fit to 2n+1 neighbouring points in time (including the point to be smoothed), with n being equal to, or greater than the order of the polynomial. After the fitting, the original and fitted values are compared, and the highest of both in maintained. The iteration step implies that once again (or multiple times) again a polynomial is fitted to the new time series. The 10-daily filtered NDVI time series were subsequently aggregated in time to obtain a monthly time series of NDVI.

The normal seasonal changes in green vegetation (NDVI) for wet and dry years were estimated on monthly basis for representative years to observe the spread and variability of vegetation cover in space and time.

Inter-annual greenness variability measurements provided greenness estimation for the study areas experiencing lower or higher vegetation cover. Then the mean monthly aggregated values were again averaged to annual values to observe inter-annual variability of greenness within Eritrea. An inter-annual vegetation cover assessment for 15-years on monthly bases was done. Inter-annual all same months mean NDVI values were calculated both temporal and spatial through aggregated pixels then evaluated its variability. This approach provided of vegetation cover fluctuations on yearly bases for the study area.

3.2.4. C-factor estimation

Soil erosion is very sensitive to vegetation cover. Vegetation cover protects the soil from raindrop impact and holds soil from runoff. Vegetation cover was assessed indirectly using a proxy of greenness (NDVI) values (Dejong, 1994). The C-factor is the cover management factor used to represents the effects of plants, soil cover, soil biomass, and soil disturbing activities on soil erosion rates. The C factor stretches between 0 and 100% based on land cover status. NDVI is positively correlated with the amount of green vegetations (Vrieling et al., 2006) which have an index of from -1 up to 1. Due to the lack of ground vegetation cover data estimation of vegetation cover using derived NDVI values was applied. Estimation of the C-factor based on NDVI variability values using a mathematical model is possible (Symeonakis & Drake, 2004; Vrieling et al., 2006). This study assumes that a linear relationship exists between NDVI and C factor. Bare soil and forest NDVI values are used as reference values. These two points gave highest and lowest NDVI values. Sample NDVI values were collected for bare soil (minimum NDVI values) and forest land cover (maximum NDVI values). The highest NDVI values observed in the NDVI time series are 0.80. Based on knowledge of Eritrea, it is assumed that these correspond to 75% vegetation cover.

Low NDVI values of 0.02 correspond to the desert areas and are assigned vegetation cover 0%. Vegetation cover was then linearly scaled between these two NDVI values. This results in the following equation:

$$VC = 0.96NDVI - 0.018 \qquad \text{Equation (8)}$$

where VC; is vegetation cover, subsequently the equation was applied to all NDVI images to convert them in to VC images.

The vegetation cover has an inverse relationship with the C-factor, the higher the vegetation cover the lower the C-factor. The derived vegetation cover has maximum and minimum values. Based on this classes and expert knowledge a C-factor determined. Kaltenrieder (2007) estimated the C-factor in the high lands of Eritrea and Ethiopia for example for cereals it is 0.15, for open forest 0.05, and continuous fallow (no vegetation protection) 1. See appendix table II for all types of crops the estimated C-factor for Eritrea and Ethiopia high lands. In this study, areas with high vegetation cover (75%) were considered to have a C- factor of 0.08 and areas that have low vegetation cover 0%, i.e. no soil protection, were assigned a C-factor of 1. Finally a linear relationship formula is established which determines the C-factor for the study area. The formula derived is expressed as:

$$C = -1.23VC+1 \qquad \text{Equation (9)}$$

where, C is cover factor and VC is the vegetation cover. Subsequently the equation was applied to all VC images to convert them in to C- factor images.

3.2.5. Spatial differences in seasonal timing of erosion risk.

Higher soil erosion usually occurs when high rainfall intensities coincide with moments of low vegetation density (Meusburger et al., 2010). Plotting of NDVI values and rainfall erosivity on the same graph on a monthly basis (1998-2012) can thus allow for an estimation of the moment of highest erosion risk. Rainfall erosivity months and seasons with corresponding vegetation cover conditions in a time series were analyzed to estimate potential soil loss. In this way, assessment was made of periods when rainfall erosivity is higher and vegetation cover is lower in space and time.

Assessments of sample pixels for representative wet and dry seasons using graphs and charts in a time series assisted to estimate potential soil erosion. To study more in detail the spatial differences in erosion risk timing, for each pixel and month the erosivity (R-factor) was multiplied with the C-factor (R*C). This follows the USLE logic where in this case only the most dynamic factors are taken in to consideration.

Soil erosion variability was assessed on normal seasonal of the wet season (June, July, August and September) on monthly bases for four representative wet (1998 and 2007) and dry (2003 and 2010) years.

To evaluate whether the approach gave reasonable results regarding the timing of erosion, results for the pixels covering the six SCRP research sites were compared with the ground data that show the multi-annual average behaviour of monthly soil loss. Hence in this way it was tested whether the R-factor and C-factor (R*C) analysis provides a good estimate of when (which month during a normal year) most erosion takes place.

3.2.6. Inter-annual variability of erosion risk

To evaluate whether the variability of erosion risk between years is high for the different regions in Eritrea, maps of annual erosion risk were prepared for each individual year (1998-2012). This erosion estimation was conducted on a monthly basis and the monthly erosion risk values were added to annual values for each year. Joint analysis of the 15 resulting annual erosion risk maps allowed for an assessment of the inter-annual variability of soil erosion risk. The soil erosion risk was prepared similarly to the monthly erosion risk maps (section 3.2.5) by multiplying the R-factor and C-factor for each month and sum monthly values. This follows the USLE approach.

To obtain a better spatial representation of erosion risk, the R*C results were multiplied with the maps of soil erodibility; and slope gradient(see section 3.1.3) through application of the "Raster Calculator" tool in the "Spatial Analyst" extension of Arc-GIS 10 using 1km2 grid for each layer. According to USLE the potential soil erosion risk includes six factors. The slope length factor (L-factor) and the management (P-factor) did not consider at this stage of assessment. For the L-factor DEM used is too coarse to accurately assess slope length, it was given to the importance of micro-relief. For the P-factor it needs detailed ground data related to management practices and the available data is limited. The formula is expressed as follows:

Potential Soil Erosion Risk = Soil erodibility * Erosivity * Slope * Vegetation cover (C-factor)

Although no plot data on annual erosion were available in this study for the same years of the satellite-based analysis, still it was evaluated whether the identified inter-annual variability of soil loss as derived from the satellite-based analysis is similar to the inter-annual variability that is shown in the ground-data. This was done for Afdeyu.

4. RESULTS AND DISCUSSION

4.1. Rainfall erosivity and its spatio-temporal variability

Annual rainfall erosivity estimates from the TRMM data (1998-2012) were compared for the Afdeyu village with ground erosivity data (1984-2002). Figure 6 shows the annual rainfall erosivity based on ground and TRMM data. From the assessment conducted the ground based rainfall erosivity is comparatively higher than that derived from TRMM-3B42. The ground based erosivity showed strong inter-annual variability with high values in 1985, 1988, 1996, 1995 being more than three times the low values of 1986, 1989 and 2002. TRMM based erosivity shows high values in 1998, 1999 and 2007 and low values for 2008, 2010 and 2012. This analysis also included five overlapped years (1998-2002). The assessment confirms that erosivity has high variability both in ground and TRMM data. The trend of time series derived TRMM erosivity line is decreasing from 1998 to 2012. This analysis is a good indication that derived TRMM data provides sufficient information for erosivity estimation in the study area.

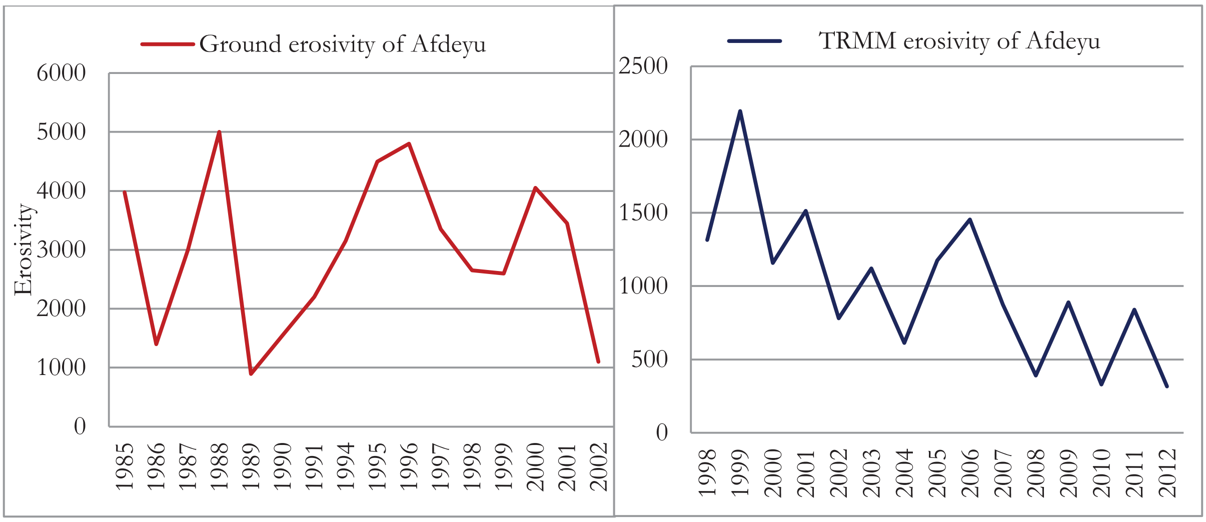


Figure 6: Annual rainfall erosivity based on ground data (1985-2002) and TRMM (1998-2012) (MJ mm/hahyr) for Afdeyu.

Figure 7 shows a comparison of the annual rainfall erosivity obtained from ground data and calculated from TRMM per-pixel for Afdeyu village for the years of overlap between both data sets (1998-2002). The scatter plot gives an R^2 of 0.64 between ground and TRMM erosivity. From the analysis conducted average ground erosivity was higher than the erosivity calculated from TRMM. In 2000 and 1999 ground and TRMM erosivity obtained is highest respectively and in 2002 both ground and TRMM results are the lowest values. Although the correlation seems weak for this estimation but still the analysis shows there is high erosivity variability on ground and TRMM data. This implies that derived TRMM data can be applicable as a substitute of ground erosivity data more over it can be useful for similar other studies.

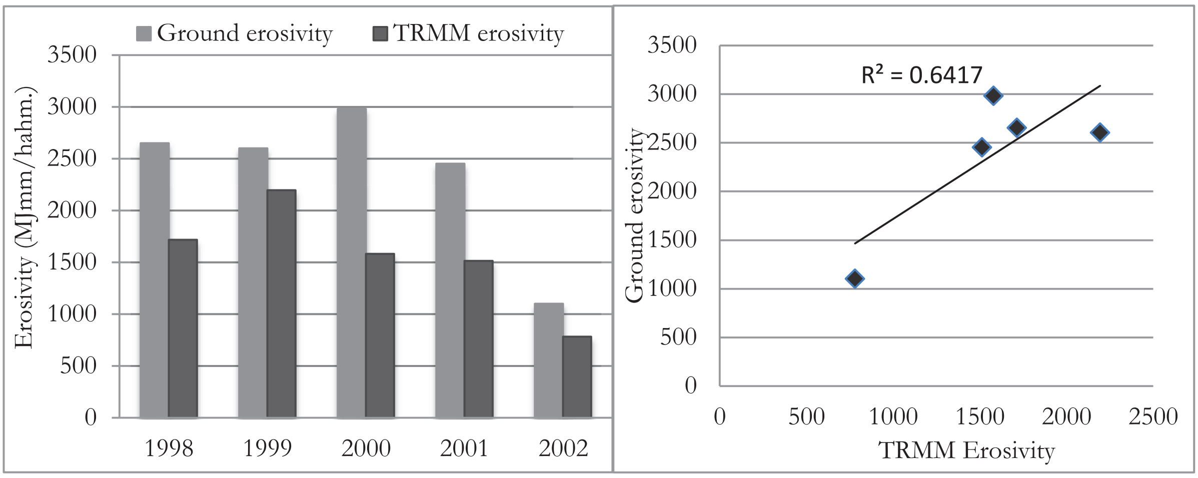


Figure 7: Comparing ground mean inter-annual rainfall erosivity and 3-hourly TRMM-3B42 inter-annual rainfall erosivity and their correlation of ground and TRMM erosivity data for Afdeyu (1998-2002).

To evaluate whether TRMM-based erosivity can provide a reasonably accurate representation of the spatial variability of erosivity, the mean annual TRMM erosivity was compared with ground erosivity for the TRMM pixels that cover the six SCRP research stations (Figure 8). For all stations ground based erosivity is higher than the TRMM derived erosivity. The highlands of Eritrea (Afdeyu) received the lowest rainfall and have the lowest erosivity measured in the SCRP sites both in ground and TRMM products. Anjeni and Gununo have the highest erosivity both from ground and TRMM data. With a positive correlation coefficient of R^2 0.34 it seems low but at least it indicates they have a positive relationship. From this comparison, TRMM-based erosivity estimates allow for a proper spatial representation of erosivity.

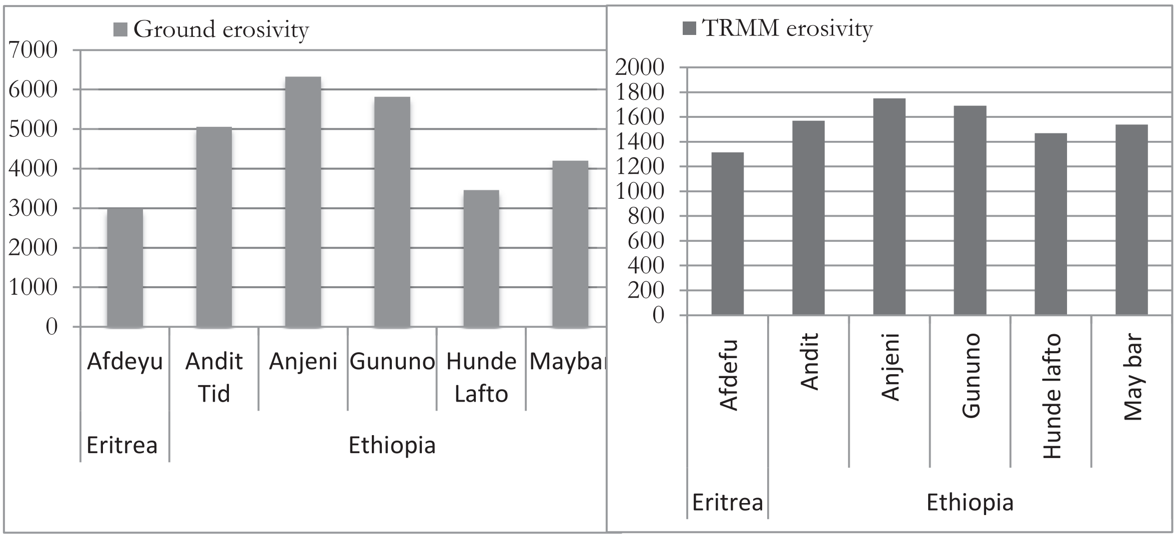


Figure 8: Estimation of ground multi-year mean rainfall erosivity (1985-2002) and 3-hourly TRMM mean rainfall erosivity (1998-2012) for six SCRP research sites.

Seasonal rainfall erosivity variability based on ground and 3-hourly TRMM data for Afdeyu village were assessed on a monthly basis. Figure 9 shows the multi-annual monthly erosivity for both ground data and TRMM data. Note that the two data sources provide averages for different years, but still both should be able to capture the normal seasonal behaviour. Again the TRMM-based erosivity estimates are clearly lower than those obtained from ground data. The rainfall erosivity is highest in the month of July and August with some extent in June and September. In the dry month's erosivity is very low to nil.

The mean seasonal rainfall erosivity obtained from ground data and TRMM analysis has a strong correlation with an R^2 of 0.84. This implies that rainfall erosivity derived from 3-hourly TRMM data is reasonably adequate to estimate the seasonal variability of erosivity for the study area.

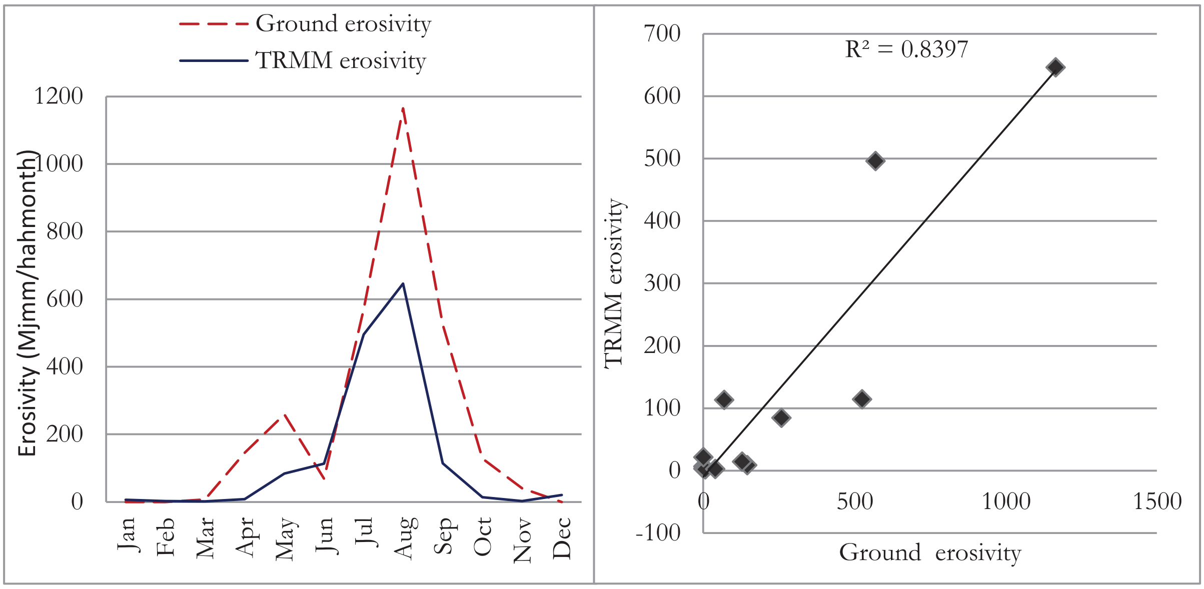


Figure 9: Estimation of soil loss using multi-year mean seasonal ground (1985-2002) and 3-hourly TRMM seasonal (1998-2002) erosivity data and regression of ground and TRMM derived erosivity for Afdeyu.

Figure 10 shows the annual erosivity maps for each individual year (1998-2012) as calculated from the TRMM data. The annual rainfall erosivity maps show a high variability of erosivity both in space and time. Generally the wetter areas (Figure 4) displayed higher erosivity values. However in some arid and semi-desert areas higher erosivity is also found in some annual maps. At the national level highest erosivity is observed in 1998, 1999, 2001, 2005 and 2007 and the lowest erosivity in 2008, 2009 and 2010. The other years shows intermediate values. Depending on agro-ecological zones moist highlands, arid-highlands and moist low lands experience the highest erosivity and arid high lands shows moderate to low values. The majority of arid low lands and semi-desert agro-ecological areas experience low to very low erosivity values. Nonetheless in 2001, 2003 and 2012 a higher erosivity is displayed in parts of semi-desert agro-ecological zones.

This assessment assisted that there is high variability of rainfall erosivity on inter-annual basis for the whole country especially the western, central highlands and southern part of the country. This variability is important to take into account when estimate the severity of soil erosion for the study area.

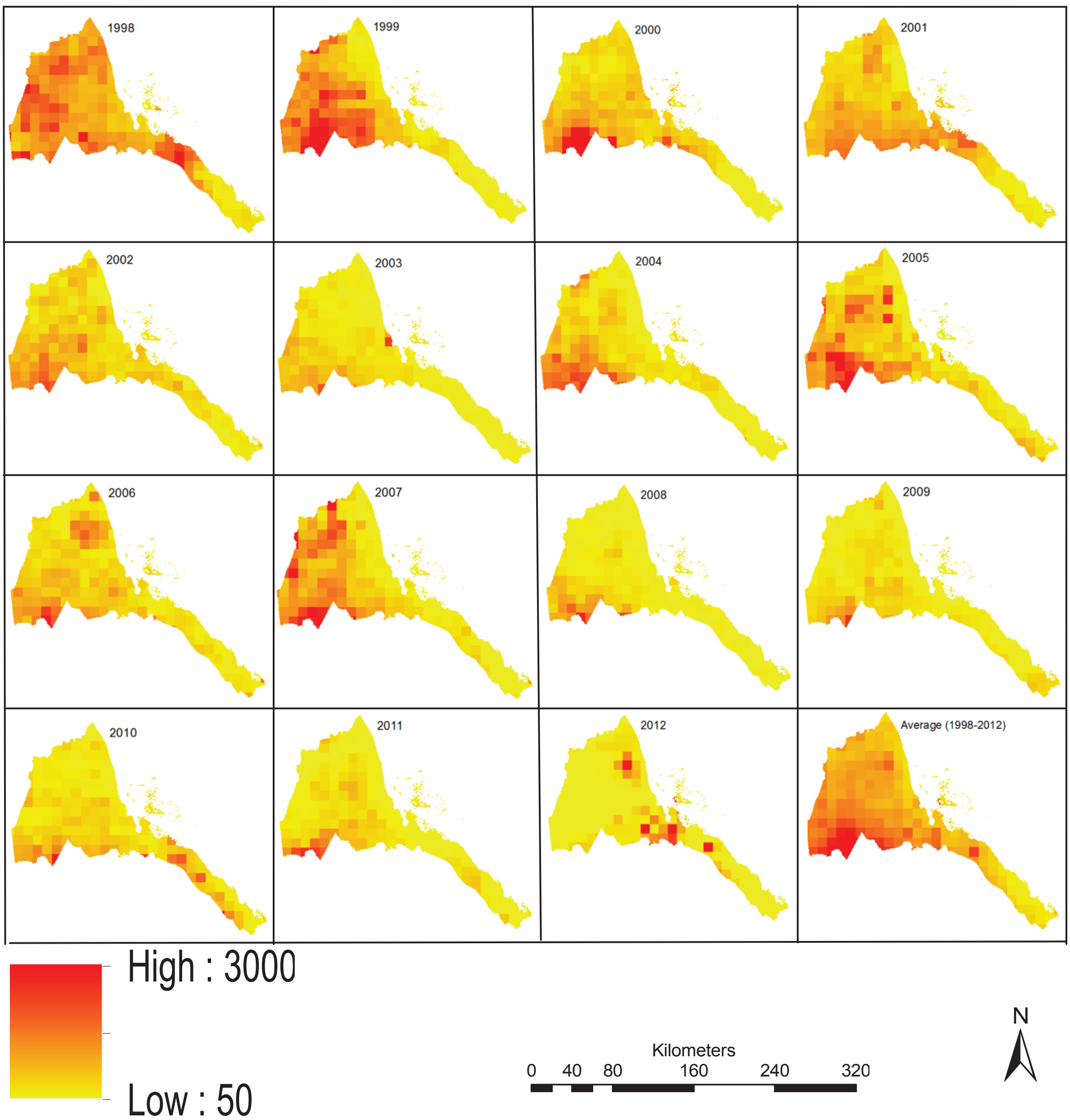


Figure 10: Inter-annual variability of rainfall erosivity (1998-2012) and average erosivity for all years (1998-2012) over Eritrea based on 3-hourly TRMM precipitation data.

Figure 11 shows the spatial and temporal variability within Eritrea of monthly rainfall erosivity for the two wettest months of the year (July and August) for the years 1998 to 2012 as obtained from the 3-hourly TRMM data. The spatial variability of the monthly values within Eritrea is represented by the first and third quartile, and the minimum and maximum erosivity. The assessment shows that erosivity shows strong fluctuations through time. The highest erosivity is observed in August 1998, 1999, 2005 and 2007. However, in some years (2001, 2009) the erosivity is higher in July than in August, which could be important if in July the vegetation is not yet well-developed. The estimated TRMM erosivity variability on a monthly basis is high.

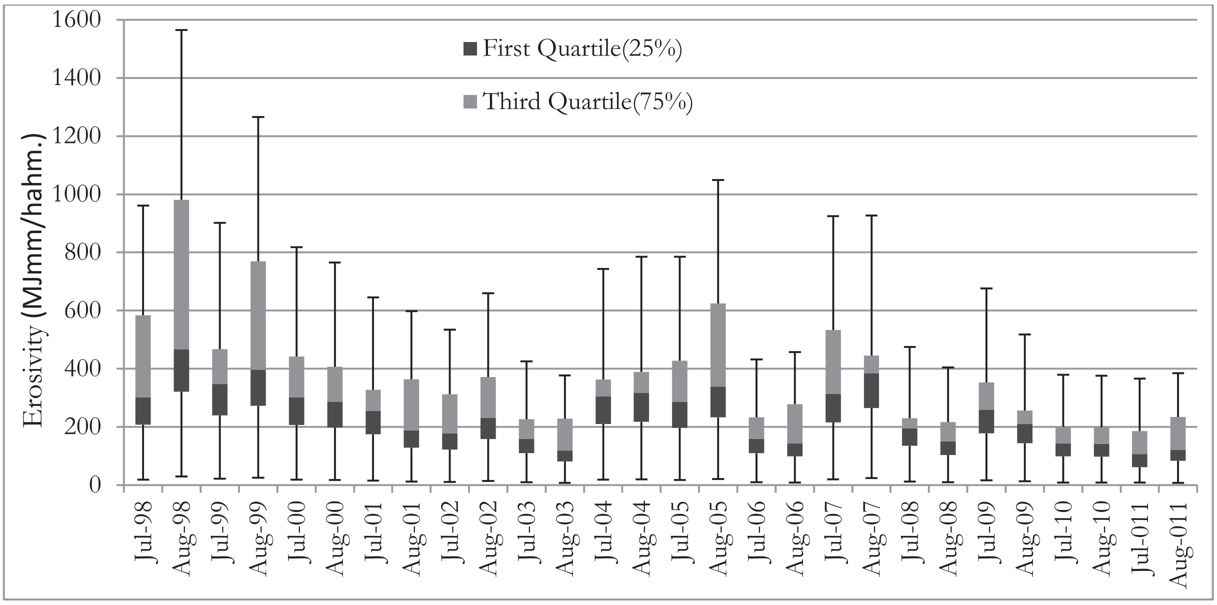


Figure 11: Monthly rainfall erosivity for the two wettest month of the year (July and August) for Eritrea (1998 to 2012).

The relationship of mean monthly rainfall and mean monthly rainfall erosivity (1998-2012) for all pixels were evaluated using a scatter plot (Figure.12). The average monthly rainfall is mostly less than 150 mm and erosivity is also mostly less than 400 MJmm/hahmonth. A high correlation coefficient shows that there is a strong relationship between erosivity and precipitation. This is not surprising, because more intense rainfall implies higher erosivity. However, at the same time we can observe a strong spread, meaning that precipitation amount is not the only important factor for erosivity, but that the distribution of rainfall intensity is clearly important as well.

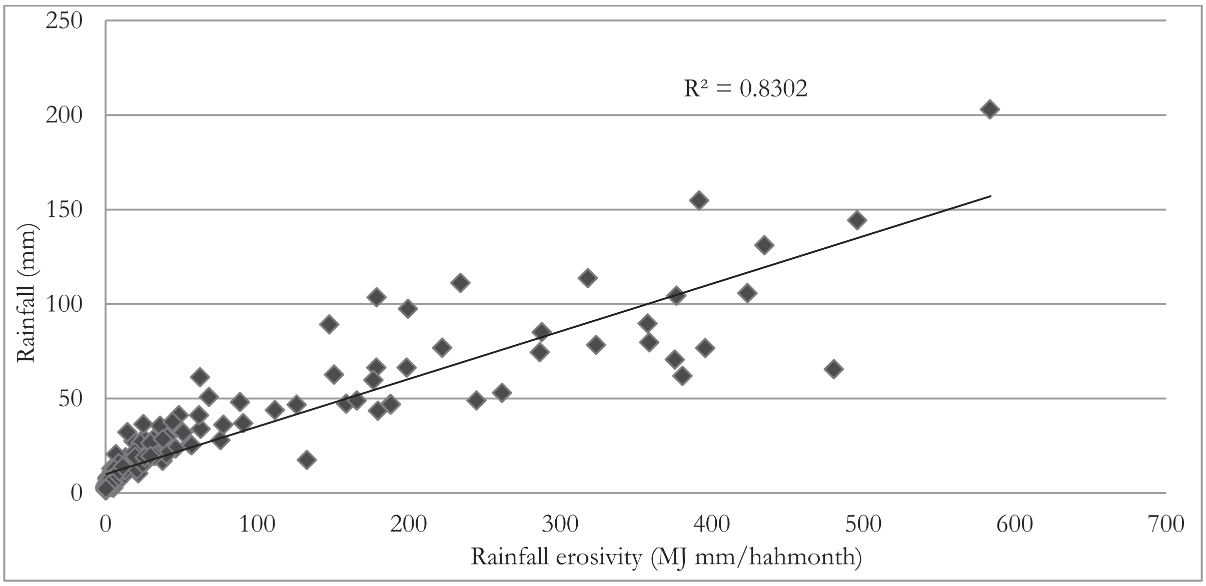


Figure 12: Correlation between TRMM-3B43 mean rainfall (mm) and TRMM-3B42 spatial mean rainfall erosivity (MJmm/hahmonth) relationships on monthly basis for all pixels (1998-2012).

The comparison between ground and TRMM derived erosivity shows that the TRMM retrievals can provide a reasonable indication of the spatial and temporal variability of rainfall erosivity. This variability is caused by climatic variations in space and time and where shown to be linked to monthly rainfall. Generally the evaluation rainfall erosivity on seasonal and inter-annual basis for the country showed high variability. Higher rainfall erosivity occurred in the major rainy season in July and August and somewhat lower erosivity was obtained for June and September. The study revealed that TRMM derived erosivity data is high in the wet (1998, 1999 and 2007) and lowest in the dry in (2000, 2003 and 2010) years. Generally, the analysis demonstrates that ground erosivity data and derived TRMM erosivity has strong relationship as a result TRMM derived erosivity data can be applicable for erosion estimation.

4.2. Spatio-temporal variability of green vegetation cover

This analysis evaluates temporal vegetation distribution of annual and inter-annual variability in a time series (1998-2012). Map of NDVI shown figure 13 have high inter-annual variability. The assessment shows all months of August, September and October have the highest NDVI values. The dry month's vegetation cover is relatively low but the sub-humid agro-ecological zone and some part of the moist highlands have abundant green vegetation cover throughout the year. Generally, the vegetation follows the rainfall meaning; an area receiving high rainfall the vegetation is relatively high. The pattern of vegetation cover increases from North and East to South and South west of the country. Moist lowlands, moist highlands and sub-humid agro-ecological zones show the highest green vegetation cover. However, semi-desert and arid lowlands have the lowest green cover.

The assessment of mean NDVI variability based on multi-years analysis assisted to identify during high and low green vegetation cover occurs in space and time. Little precipitation usually starts in June then reaches highest in July and August. Rainfall falling in June and July is critical as the ground has less protection and the land is prepared and cleared to be ready for cultivation consequently severe erosion is expected in these months. However, in August up to September the vegetation cover increases then reaches highest the ground is relatively fully protected from water erosion. The green vegetation cover majority of the country shows very low. In this case the highest NDVI index recoded from the classification is 0.8 and the lowest is 0 NDVI. This high green cover stays for a short season (four months with in 12 month of the year). This green vegetation cover (NDVI) is mostly annual vegetation cover. During dry season or crop harvesting the cover decreases.

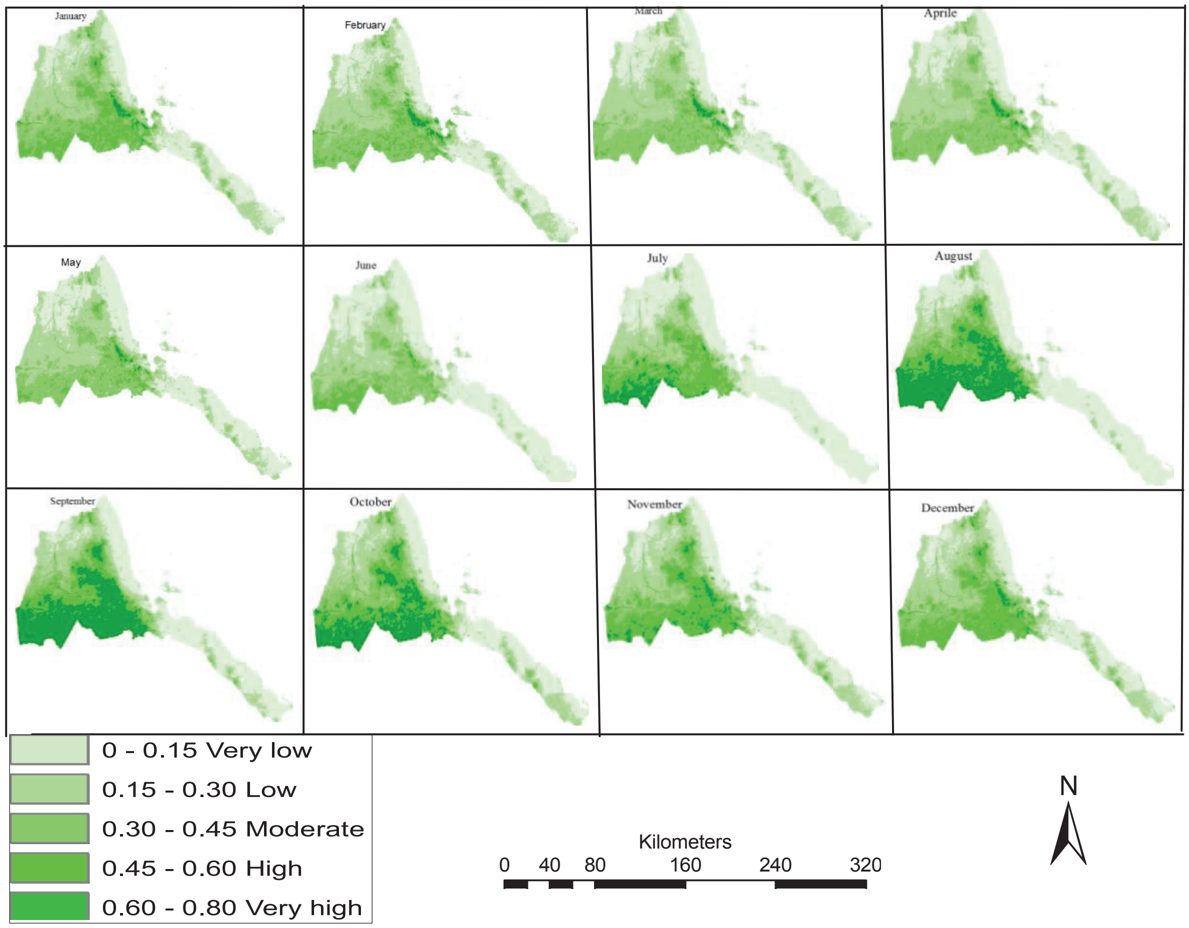


Figure 13: Multi-year (1998-2012) average monthly NDVI for Eritrea, representing spatially the normal seasonal NDVI variability.

This vegetation cover derived from mean NDVI was assessed on monthly and seasonal bases for wet (1998 and 2007) and dry (2003 and 2011) years. In July vegetation cover starts to grow then reaches highest in months of August and September. The vegetation cover evaluation of wet years (1998 and 2007) have significantly higher cover than the dry (2003 and 2011) years. The vegetation cover in figure 14 demonstrated much variability between June and September. The highest vegetation cover was in August and September with moderate in July and lowest cover in the starting of rainy season (June) for all the months. The assessment indicated that the green vegetation cover for the study area have huge variability both in space and time. The assessment shows vegetation cover for most of the study area is low even in the wet season especially the areas of semi-desert (coastal areas) and arid low lands the green cover is very low. In June and July there is less vegetation protection and large field is disturbed for farming practices probably higher erosion takes places in these months. From the analysis performed the highest vegetation cover is observed in moist lowlands and moist highlands and the lowest covered areas are arid low lands and semi-desert (coastal areas). The vegetation classification estimation showed the highest cover is 75% and the lowest is 0%.

Figure 14: Monthly vegetation cover (%) as estimated from SPOT-VGT NDVI for three dry (2001, 2003, and 2011) and two wet (1998 and 2007) years.

4.3. Seasonal timing of erosion risk and its spatial variability

Erosion risk is high when high rainfall erosivity coincides with low vegetation cover. Figure 15 shows the combination of rainfall erosivity and green vegetation cover (NDVI) of wet (1998 and 2007) and dry (2003 and 2010) years and the average mean NDVI values of the four years. In mid June up to July erosivity increases but NDVI values are low at this period especially for the dry years. Mean erosivity of the four years reached peak values in August and NDVI in mid September. Erosivity started to drop in the beginning of September while vegetation cover increases thus runoff and soil erosion was expected to decrease starting from months of August. The assessment indicated that highest soil loss were occured from mid-June up to August. Therefore most soil erosion can be expected to occur in months of July and August, when erosivity is highest and vegetation is not yet fully developed.

The analysis displays that soil erosion is accelerated when preparing the land for production of food and fibre and that soil erosion decreases exponentially with increasing ground cover. In some years vegetation is still poorly developed when already high erosivity occurs which usually results high soil loss.

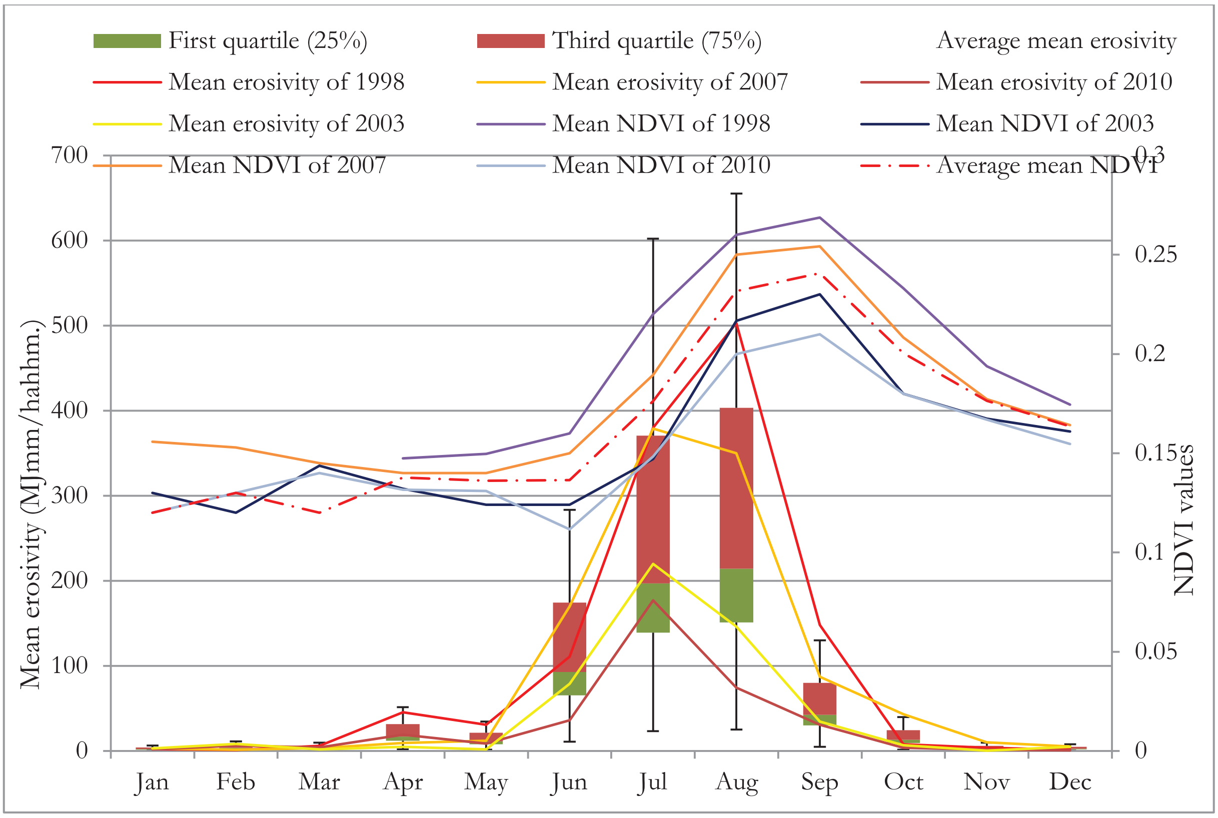


Figure 15: Seasonal variability of erosivity and NDVI, spatially aggregated for the whole of Eritrea; for an average year, and wet (1998 and 2007), and dry (2003 and2010) years.

Figure 16 shows the assessments of erosion was done by direct multiplication of R-factor with C-factor by taking representative years from the time series (1998-2012) analysis. Potential soil loss of R*C for the study area starts to develop in April then reached highest peack in August. The result shows that soil loss is siginificantly higher in wet season than dry seasons. For example in wet (1998 and 2007) years the soil loss is higher than the dry (2003 and 2011) years. In 1998 erosion (R*C product) is the highest values recorded. In 2007 in the month of June higher erosion is observed but in July figure 16 and 19 August-2007 map shows similar decreasing erosion risk patterns then and drops up to August due to vegetation cover increases in this months. However in 1998 in June erosion is very low and reaches highest peack in August. Some times in June unexpected high erosion occurs as figure 16 shows again R*C producets indicate high soil loss. The assessment confirmed that for the study site high erosion risk months are July and August, low erosion risk in months of June, September to October and very low erosion risk in dry season. Least potential soil erosion areas and months occurred in the dry season could be as a result of relatively low rainfall intensity and high vegetation cover. The high soil erosion risk occurred in the major rainy season could also be explained by high rainfall intensity and low vegetation cover. The assessemnt of soil erosion showedthere is high seasonal and inter-annual variability.

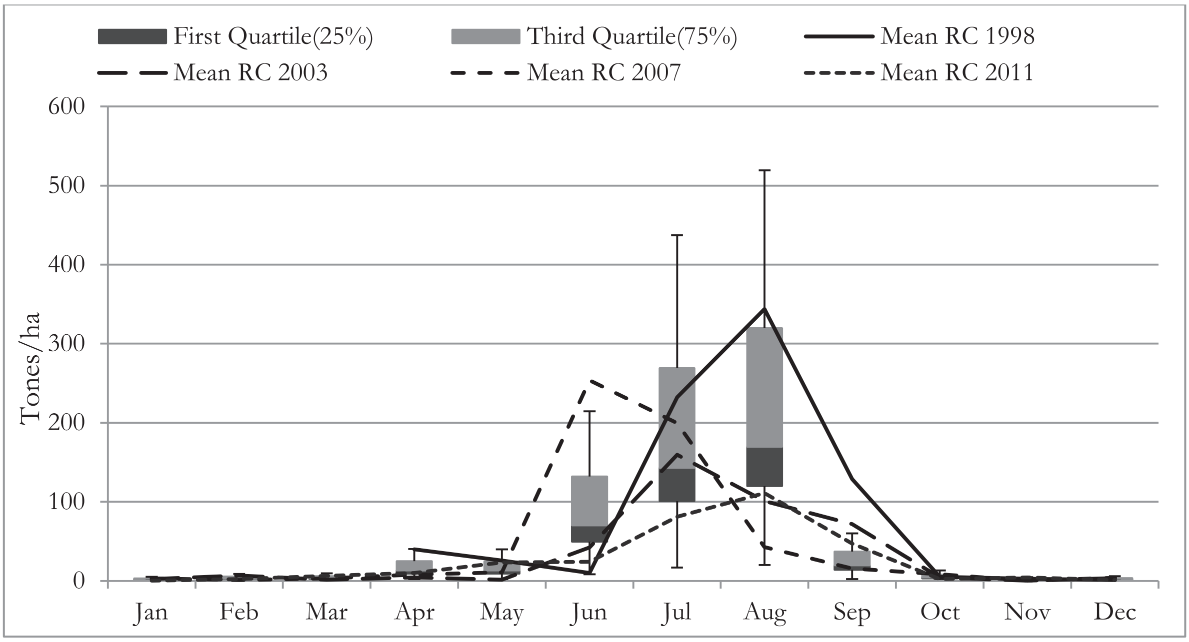


Figure 16: Potential soil erosion estimation for wet (1998 and 2007) and dry (2003 and 2011) years. The box plot shows the multi-year average, first quartile and third quartile with the whiskers indicating the minimum and maximum values.

Figure 17 shows that potential soil loss of R*C and ground soil loss both for Afdeyu areas. This assessments was based on seasonal ground soil loss and satellite prediction (R*C) soil erosion. The R*C was done by direct multiplication of R-factor with C-factor by taking representative years from the time series (1998-2012) analysis. The result shows that soil loss estimated from satellite is siginificantly higher than ground based soil loss.

The analysis confirms that soil loss is higher in wet season than dry seasons for both products. Inthe case of satellite estimation (R*C) of wet (1998 and 2007) years the soil loss higher than the dry (2003 and 2011) years. In 1998 erosion (RC product) is the highest values recorded. In 2007 in the month of June higher erosion is observed but in July the erosion risk decreases and drops up to August may be due to vegetation cover increases in this months. The average (mean multi-year) erosion product shows it started from May then reached peak in August. So this indicates that erosion is always intense with varying the degree of severity. However in 1998 in June erosion is very low and reaches highest peack in August. Some times in June unexpected high erosion occurs in both products as figure 17 shows again in ground and RC products indicate high soil losses. The ground soil loss indicates test plot 2 and 3 shows highest soil loss. This test plots are low in slope that used for cultivation test plots. The other test plots are grazing and rocky areas having steep slope and less soil loss. This confirms that seasonal factors and human interference for cultivation like land clearing do have high influence in facilitating for soil erosion processes. The calculation concludes that highest soil loss is observed in months of July and August.

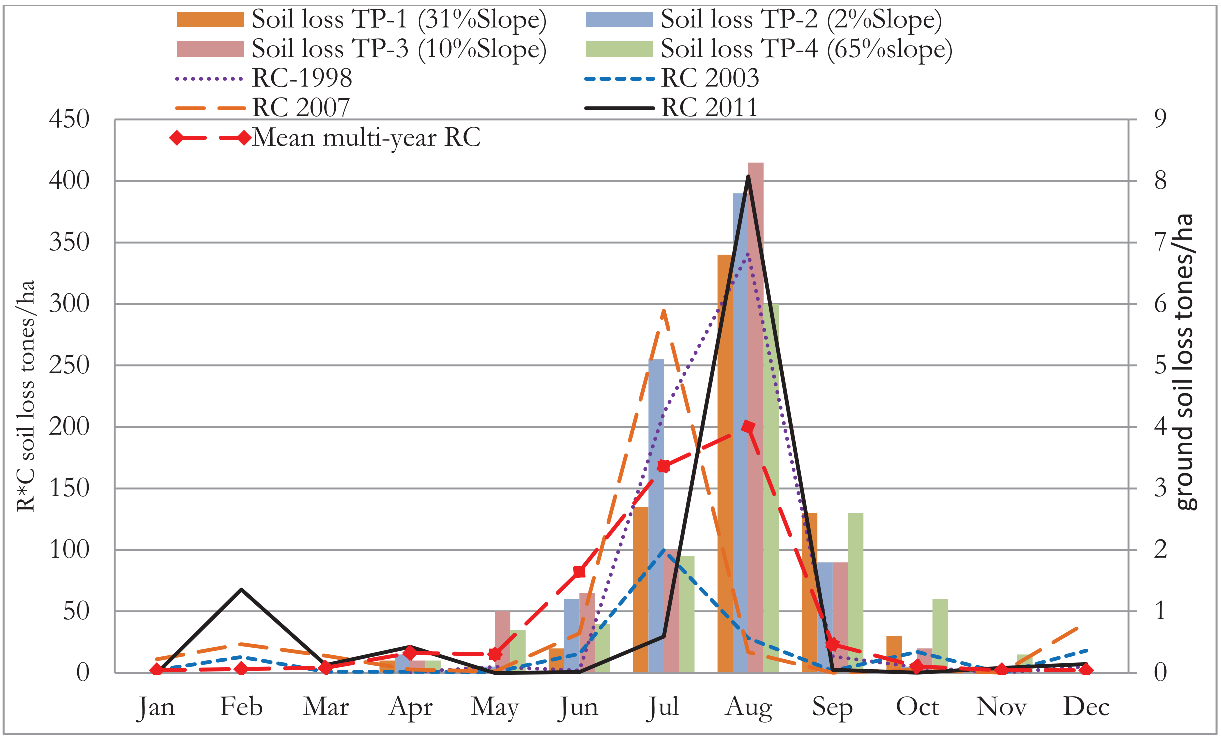


Figure 17: Potential soil erosion estimation (R*C) per-pixel (38.876E , 15.497N) for wet (1998 and 2007) and dry (2003 and 2011) years and ground soil loss tones/ha for Afdeyu (Herweg & Stillhardt, 1999).

Figure 18 shows the relationship of ground soil loss and satellite predicted soil loss for Afdeyu area. The analysis indicates that both have strong correlation with R^2 0.77. This implies that remote sensing application for erosion estimation is applicable.

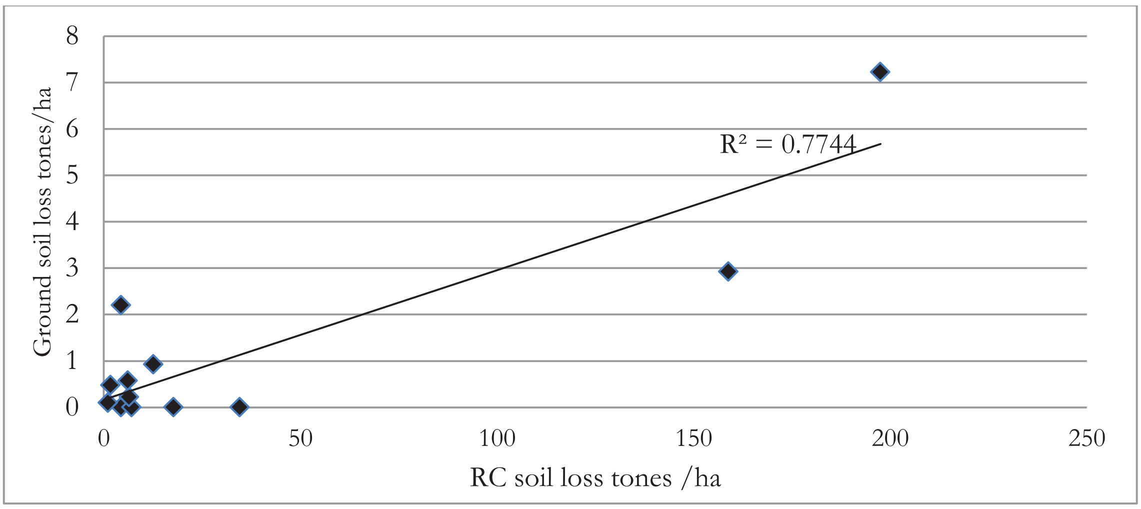


Figure 18: Multi-seasonal soil loss estimation with regression line and R- correlation between ground soil loss and R*C product

Rainfall erosivity and and vegetation cover are changing in space and time frequently. This analysis is then conducted by taking the most dynamic soil erosion factors that influence critically. Figure 19 shows an estimation of soil erosion results obtained using the direct multiplication of R-factor and C-factor (R*C). This assessments provided the importance of assessing seasonal variability of soil erosion in wet (1998 and 2007) and dry (2003 and 2007) years. In general erosion appreas to be high in the wettest (1998 and 2007) than dry (2003 and 2011) years. However, this is not consistent for some areas and some times there is an exception in July - 2003 and August - 2011 high erosion takes place. The months with higher erosion values for the area are July and August with some extent in June and September. The map analysis indicated that moist low lands, moist high lands and some part of arid low lands soil erosion has been frequent and severe and also the erosion variability is very high both in time and space. This suggests that rainfall intensity is more important than amount of rainfall for erosion studies.

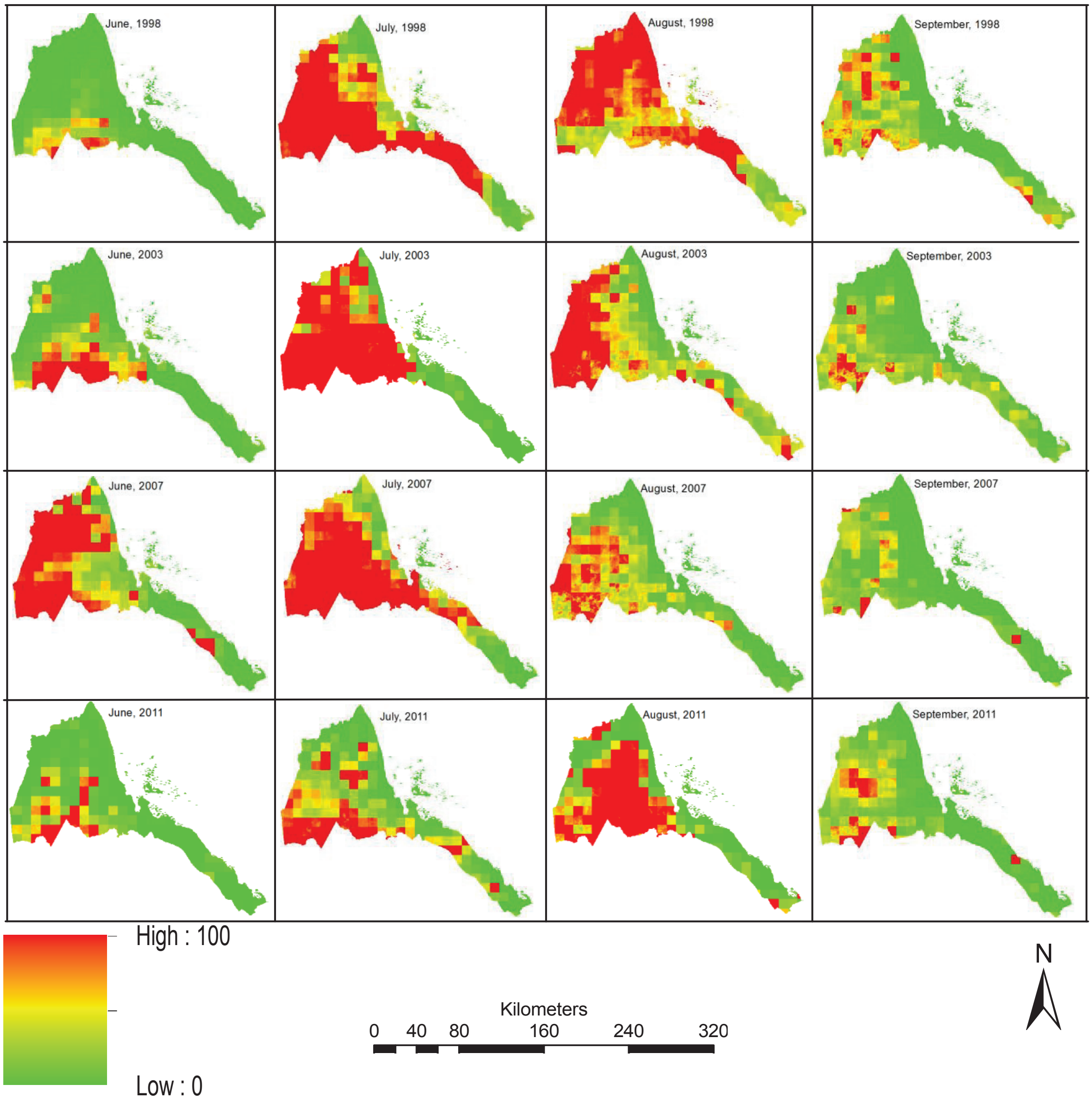


Figure 19: Seasonal potential soil erosion estimation (R*C) on monthly bases for wet (1998 and 2007) and dry (2003 and 2011) years.

4.4. Inter-annual variability of erosion risk

Figure 20 shows the estimated potential soil erosion risk maps having high variability on annual basis. High soil erosion predicted areas can be accounted for in terms of the steep unstable terrain, the highly erodible soils, high rainfall erosivity and low vegetation cover. For this high variability can be due to seasonal factors such as changing of rainfall patterns and intensity and vegetation cover fluctuations.

The assessment assisted that in wet year's potential soil erosion was significantly higher than the dry years. This high erosion rate could be attributed mainly to the steep slopes characteristic of the area, as well as to the relatively high rainfall intensity. Most of the high erosion risk zones are located in steep slope and high elevation as well as in areas having high erosivity experiencing places such as moist highlands, moist low lands, and sub-humid and arid high lands showed high erosion risk. Especially arid highlands soil erosion is severe due to low vegetation cover and steep slopes than the moist highlands that have relatively high vegetation cover and less steep slope. Most of the arid low lands and semi-desert agro-ecological zones and areas having low/flat slope gradients the potential erosion risk were low as indicated in (figure-20). Generally the estimated annual potential soil erosion risk maps shows areas having higher elevation demonstrate very high erosion. These areas are the hotspots often visible in the calculated average annual maps. These are mountainous areas, having limited vegetation cover and the rainfall regime is highly varied and aggressive.

The assessment of potential soil erosion risk (hot spot) areas are not consistent there were high variation inter-annually due to seasonal factors. For example in wet (2007) year there appears to be high erosion also in the dry (2003 and 2011) years there is also high erosion but in moderate rainfall (2008 and 2010) years the potential erosion is low this is clearly due to climatic or seasonal variability. In year 2012 the erosion is low due to all the months of the years are not considered. In some years the rainfall is very erosive and in some years it is less aggressive. That's why the high variability is constantly displaying for the annual soil erosion risk maps of the country. Conversely, the predicted areas of low soil erosion reflected the lower relief, the greater density of the vegetation canopy and the areas receiving low precipitation. Areas showing low potential erosion can be explained by the absence of heavy rainfall storms such as North West and coastal areas of the country.

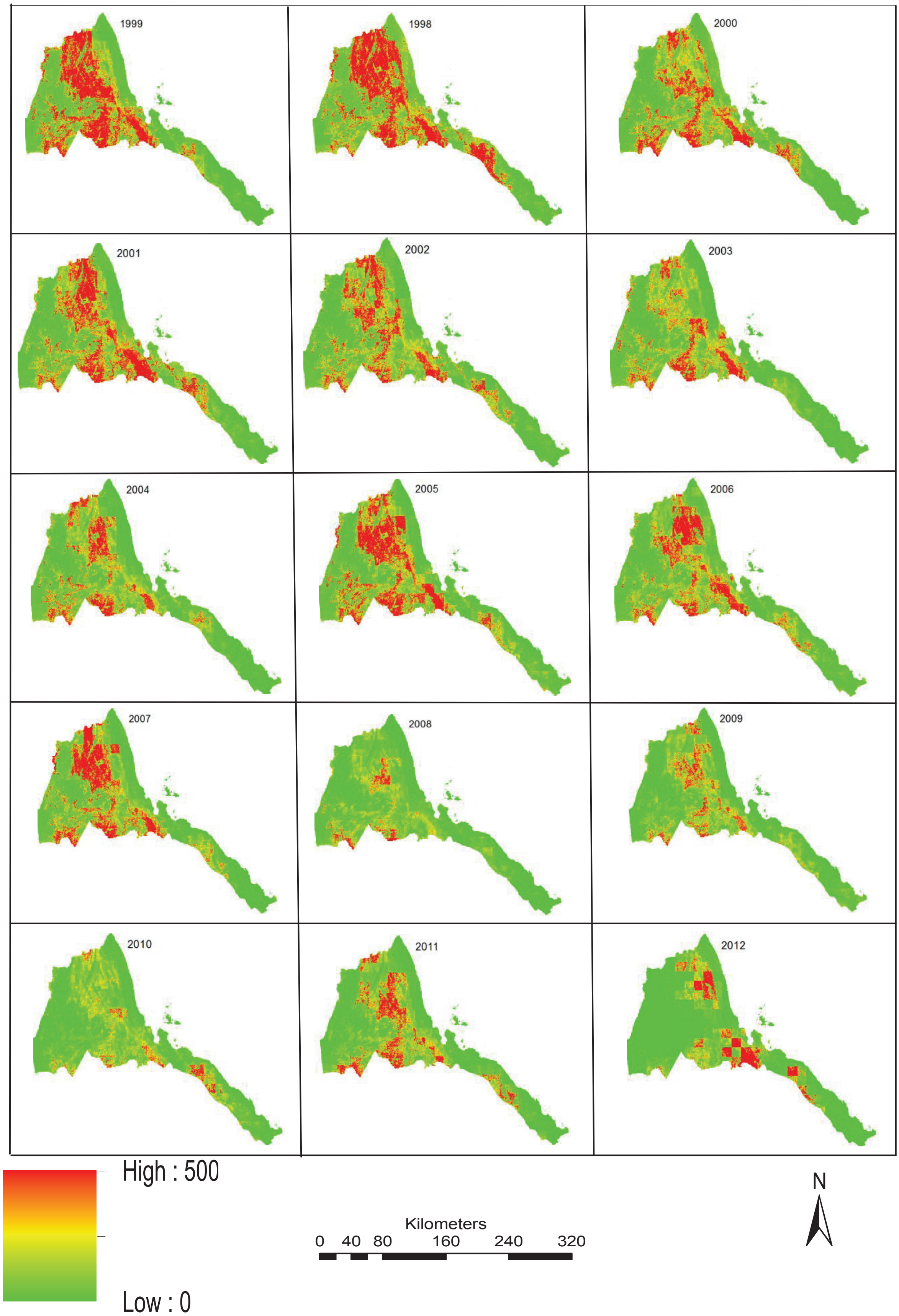


Figure 20 : Annual potential soil erosion risk maps (1998 - 2012).

Figure 21 shows the estimation of soil erosion for all year's (1998 up to 2012) average; maximum, minimum, and as well as standard deviation. The maximum erosion appears to be most dominant all over the country and the minimum erosion risk map indicates that arid highlands and moist highlands minor erosion risks are visible. Most of the country demonstrated low erosion risks. The standard deviation shows there is high variability of temporal and spatial potential soil erosion over the study areas. This is due to seasonal extremes that frequently occurred in the country, the standard deviation map shows high variations of erosion risk areas.

The evaluation of erosion risk maps showed there is high variability and it's severe all over the study areas. Especially moist highlands and arid highlands as well as most part of moist lowlands soil erosion is intense. The analysis suggests that during maximum rainfall intensity sever erosion occurs that erodes large land area which usually affects land productivity of the study area.

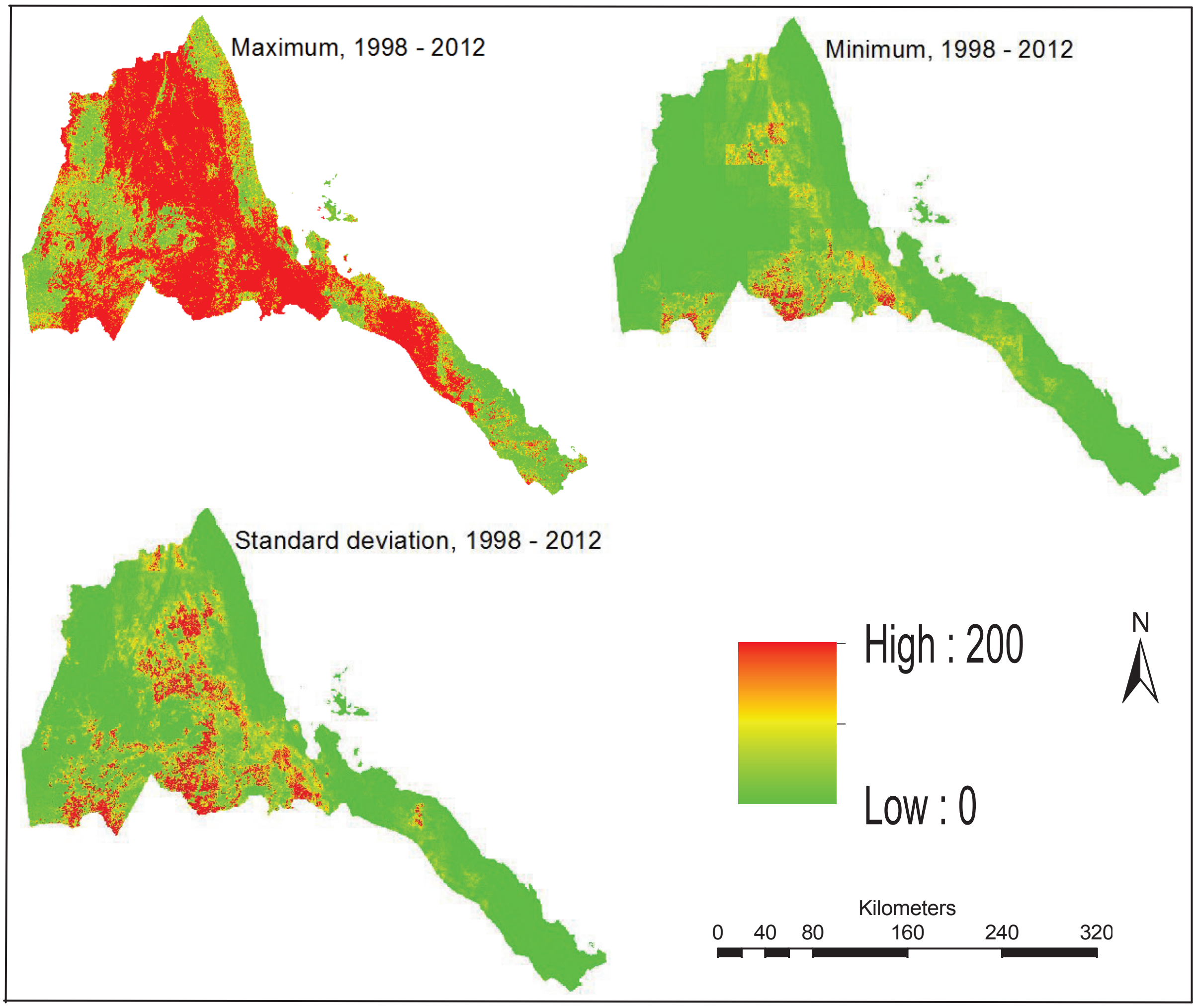


Figure 21 : Annual potential soil erosion risk maps maximum, minimum, and standard deviation for all years (1998 up to 2012).

4.5. Discussion

This study estimated the variability of rainfall erosivity and green vegetation cover in time and space using freely available coarse-resolution satellite imagery. These two factors are the most dynamic erosion factors in nature over time and space. The purpose of this study was to estimate spatial and temporal patterns of both erosion factors for Eritrea.

Ground data of six soil conservation research program (SCRP) research sites were used to evaluate whether seasonal and inter-annual variability of erosivity and soil loss is well captured by the coarse-resolution data analysis performed in this study.

Comparison of the TRMM derived rainfall erosivity with the ground erosivity data revealed that TRMM underestimates erosivity. Main causes could include the coarse-spatial resolution of the TRMM data which cannot fully captures the very high rainfall intensities that occur at localized scales. In addition, the 3-hourly rainfall intensity data may not provide a good enough description of peak intensities Within Eritrea, the estimated average annual erosivity ranged from 50 MJmm/hahyr to 3000 MJmm/hahyr. The multi-year mean erosivity ground data of Afdeyu is 2300 MJmm/hahyr (Haile et al., 2006) and the TRMM assessed multi-year mean erosivity values for Afdeyu the overlapping years (1998-2002) is 1315MJmm/hahyr with a moderate coefficient of correlation 0.64. Therefore it can be confirmed that areas receiving around 3000 MJmm/hahyr the predicted risk of erosion is severe.

The estimation of rainfall erosivity conducted shows that there is huge variability in monthly and yearly basis. For example in Afdeyu One intense single rainfall event caused almost 100 % of the total monthly soil loss (40.8 of 41.5 t/ha), e.g. the event of 27 July 1988 with 89.1 mm of rainfall and an erosivity of 187.7 J/mh (Stillhardt et al., 2002). And the TRMM derived mean rainfall and mean erosivity for Afdeyu village calculated for two representative months (July and August) (1998-2012) were 130 mm and 306MJmm/hahmonth respectively. This analysis assisted that it's not the amount of rainfall that causes erosion but the most important is the intensity of rainfall. The research conducted in Afdeyu and six stations in Ethiopia showed; the energy of a rainfall for one drop size is more aggressive in the Eritrean and Ethiopian highlands than any other areas (Nyssen et al., 2004). Therefore, the rainfall is generally erosive and it is relatively higher in wet years than dry years. But it is not always consistent in some dry years higher erosivity is occurred. The months of highest rainfall erosivity were July and August and to a lesser extent June and September in the dry months it's very low. On average annual bases; in 1998, 1999, 2005 and 2007 are the highest erosivity calculated and the lowest erosivity years are; 2003, 2008, 2009, 2010 and 2011. The remaining years have an intermediate values. The rainfall erosivity generally decreases towards North, North West and East direction of the study area. And higher erosivity experiencing areas are central high lands, south and south-west of the country. The amount of precipitation also showed the same distribution pattern. The rainfall over the study area is aggressive, and the distribution also has high variability. Least erosivity values occurring in the dry season could be explained by relatively low amount of rainfall.

The second time dependent erosion factor which is vegetation cover was assessed and studied its variability over the study area. The estimation of vegetation cover or the proxy of greenness (NDVI) in Eritrea showed high variability in space and time. According to J. Nyssen et al. (2005) rainfall and vegetation cover are the factors that show strong intra-annual variability in the highlands of Eritrea and Ethiopia. The months of highest green vegetation cover are August and September to a lesser extent July and October. In the dry months green vegetation is very low all over the country. Areas that have abundant vegetation cover during wet seasons are highlands (sub-humid and moist highlands) and western moist lowlands. In general, green vegetation cover decreases towards the North, North West and East. Especially in the arid lowlands and semi-desert agro-ecological zones the vegetation cover is very low. Most of the vegetation cover is seasonal. For example according to Stillhardt et al. (2002) the total arable land of Afdeyu village 60% is covered by cereals like maize and barley before cultivation and after harvesting the fields remain open. As a result green vegetation cover often fails in this area to produce sufficient ground cover during the onset of the rains after the dry season or drought period. Consequently most erosion takes place during the transition period of farming like land preparation and clearing for planting and sowing. In August ground cover increases then erosion decreases in some years but usually from the analysis in August heavy rainstorms are available the expected erosion is also high. The assessment done shows green vegetation cover for the whole country is generally low especially during dry periods.

Normally, plant protection reduces soil erosion and increases aggregate stability of soil due to increase of organic matter. In Eritrea at the start of the rainy season the green vegetation cover has not yet well-developed while high-intensity rainfall causes high soil loss; hence normally most erosion is expected to take place during this period. For example according to Symeonakis and Drake (2010) in Eritrean central highlands May, i.e. the beginning of the wet season, vegetation covers a small part of the surface (3%) and therefore the relatively low amount of rainfall (70 mm) is enough to cause the highest amounts of overland flow and erosion (17 and 16mm respectively) for the year. After two months, in July, the same (70 mm) amount of precipitation leads to less overland flow and erosion (5 and 9mm respectively) due to the doubling of the vegetation cover in this period (6%). The estimation conducted on monthly vegetation cover provided most of the study area have very low cover but during wet season from mid-July up to October the cover is high in the central and western part of the country. Therefore the risk of erosion decreases. However from the SCRP test plot experiments recorded shows that; soil losses were 10 t/ha during high erosive rainfall periods with 65% plant cover, while 5 t/ha were observed at different stations, even with 75 to 85% plant cover (K.; Herweg & Eva Ludi, 1999).

In some years vegetation is still poorly developed when already high erosivity occurs which usually results high soil losses. For example figure 16 shows in June there is high erosivity but the green vegetation cover (NDVI) is lowest the whole month. Consequently the predicted soil loss is high in this month.. The greatest or high potential soil erosion risk occurred in the major rainy season could also be explained by high rainfall amount, steep slopes, highly susceptible soils. High erosion in contrast to the low-lying areas, it has greater rainfall amplitude and intensity (Ogbazghi et al., 2011). Least potential soil erosion areas and months occurred in the dry season could be as a result of relatively low amount of rainfall and flat areas as well as less susceptible soils. Moreover, vegetation cover and thus erosion risk, can be highly variable during the year, depending on seasonal effects and land management (Vrieling et al., 2008). Soil loss and erosivity of rainfall are linked, this could be due to different onset of rainfall: a year with high rainfall intensity might be characterized by a crop vegetation cover not yet well established, which increases soil erosion; a year with later heavy rainfall might be characterized by a better established vegetative protection and less erosion (Ogbazghi et al., 2011).

The constructed soil erosion risk maps indicate that soil erosion was most serious in the moist highlands, arid highlands and sub-humid zones and very important in some parts of moist low lands agro-ecological zones. Erosion rates were relatively low in most parts of arid low lands and semi-desert agro-ecological zones (coastal areas). The spatial/map pattern of monthly soil erosion shows that the predicted areas of high soil erosion can be accounted for in terms of the steep unstable terrain, the highly erodible soils, high precipitation and low vegetation cover. According to Symeonakis and Drake (2010) the high erosion rate in the Horn of Africa can be attributed mainly to the steep slopes of the area, as well as to the relatively high amount of rainfall. Conversely, the predicted areas of low soil erosion reflected the lower relief, the greater density of the vegetation canopy and the areas receiving of low precipitation.

The evaluated potential soil erosion showed high variability on monthly and seasonal bases. The assessment confirmed that rainfall erosivity and vegetation cover determined for the study site reveals a high potenial erosion risk in rainy season (July and August); low erosion risk in low rainy season (April, June, September to October) and very low erosion risk in dry season. Least potential soil erosion areas occurred in the dry season could be as a result of relatively low amount of rainfall. The greatest or high potential soil erosion risk occurred in the rainy season could also be explained by high rainfall intensity and limited vegetation cover especially in July and August. However, in some years as the vegetation cover increases the soil loss predicted is low.

The estimated monthly and average annual potential soil erosion risk maps were expressed in qualitative terms rather than in actual rates of soil loss at the national scale, using the USLE methodologies. The reason for this is that a quantitative assessment is not really appropriate with the available data, and the erosion risk was assessed in terms qualitatively. Moreover, quantitative analysis is expensive and time consuming. The model did not intended to estimate the amount of soil loss and sediment yield but to provide potential erosion risk maps for the analysis of planning and environmental protection. Besides, the model can provide the decision makers in the areas with erosion risk so that they can develop soil and water conservation plans in general and generate detailed erosion studies for the areas of high erosion risk.

The effects of management practice for estimation potential soil erosion is not directly included in this analysis such practices are contouring, strip-cropping, terracing and subsurface drainage. These practices can be included in a so called support practice, p-factor. A proper spatial distribution of management practices across Eritrea is nearly impossible to obtain based on available ground data or remote sensing datasets. However, it should be realized that management practice may be one of the most important factors affecting erosion in many cases.

For soil erosion protection purposes all woody and non-woody materials whether they are green vegetation or dead vegetation like grasses, dead tree leaves are useful for surface protection. Therefore, one clear limitation using NDVI values as an indicator of vegetation cover was that it does not account for senescent vegetation and another limitation that it does not differentiate between differences of vegetation types in their effectiveness to protect the soil. In this study the vegetation cover was estimated using an arbitrary scaling (very high and very low NDVI points). Then based on the vegetation cover percentage a C-factor was estimated. Although this approach clearly has limitations, nonetheless it allowed for a reasonable description of temporal changes in the protective vegetation cover across Eritrea.

For erosion risk mapping activity the timing of satellite images is useful to be considered in relation to the erosive season. The importance of seasonal and inter-annual soil erosion assessment is to confirm areas that have similar in climatic regime and vegetation development, which assisted to determine whether the high- erosion period is always at the same moment. Moreover, it assisted to identify areas of erosion hot spots and the timing of occurrence of severe erosion in large areas within a short time and with relatively low coast. Therefore, investigation of inter-annual variability was necessary to distinguish long term trends of vegetation cover and rainfall erosivity. It helps also to observe the changes caused by seasonal variability and human interferences of an area.

5. Conclusion and Recommendation

The study demonstrated that regional erosion studies can be performed using multi-temporal satellite imagery. Such an approach is relevant especially for countries like Eritrea that otherwise has limited ground data availability on important erosion-controlling factors like rainfall, vegetation cover, land use, and soils. In general the study illustrates that timing of satellite images for erosion risk mapping is important. The analysis of multi-temporal images such as rainfall erosivity and vegetation cover is vital for large areas for erosion assessments at national scale. To estimate when erosion risk is high in the study area the coarse-resolution data analysis on vegetation (SPOT-VGT NDVI, TRMM) rainfall erosivity (TRMM) provided useful insights. There is a possibility of using that timing information to make higher-resolution erosion maps by selecting high-resolution satellite data from the most relevant months.

Ground-based rainfall erosivity values obtained from different literatures used for partial validation process for the 3-hourly TRMM derived rainfall erosivity. The analysis conducted showed that the timing of erosion in Eritrea using ground information and derived satellite data occurred on the same moments. That is both ground based prediction and remote sensing analysis identified that highest erosion risk periods are July and August with some extent in June and September. In both erosion models there is high variability seasonally and inter-annually due to seasonal factors.

For erosion risk mapping activity the timing of satellite images is use full to be considered in relation to the erosive season. The main importance of inter-annual soil erosion assessment is used to confirm areas that have similar in climatic regime and vegetation development, which assisted to determine whether the high- erosion period is always at the same moment. Estimated rainfall erosivity derived TRMM data and vegetation cover dynamics provided the importance of assessing the monthly, normal seasonal and inter-annual variability of potential soil erosion pattrerns.

For this analysis minor limitations have been displayed such as the lack of complete validation data or detailed and continuous ground erosivity data and NDVI is only sensitive to green healthy vegetation so it excludes the senescent vegetations.

List Of References

Angulo-Martinez, M., & Begueria, S. (2009). Estimating Rainfall Erosivity From Daily Precipitation Records: A Comparison Among Methods Using Data From The Ebro Basin (Ne Spain). *Journal Of Hydrology, 379*(1-2), 111-121. Doi: 10.1016/J.Jhydrol.2009.09.051

Boerma, P. (2006). Assessing Forest Cover Change In Eritrea: A Historical Perspective. [Research Article]. *Mountain Research Development, Vol 26 No 1 Feb 2006: 41–47*, 41–47.

Bouaziz, M., Leidig, M., & Gloaguen, R. (2011). Optimal Parameter Selection For Qualitative Regional Erosion Risk Monitoring: A Remote Sensing Study Of Se Ethiopia. *Geoscience Frontiers, 2*(2), 237-245. Doi: 10.1016/J.Gsf.2011.03.004

Butt, M. J., Waqas, A., Mahmood, R., & Cshrg. (2010). The Combined Effect Of Vegetation And Soil Erosion In The Water Resource Management. *Water Resources Management, 24*(13), 3701-3714. Doi: 10.1007/S11269-010-9627-7

Chen, J., Jonsson, P., Tamura, M., Gu, Z. H., Matsushita, B., & Eklundh, L. (2004). A Simple Method For Reconstructing A High-Quality Ndvi Time-Series Data Set Based On The Savitzky-Golay Filter. *Remote Sensing Of Environment, 91*(3-4), 332-344. Doi: 10.1016/J.Rse.2004.03.014

De Asis, A. M., & Omasa, K. (2007). Estimation Of Vegetation Parameter For Modeling Soil Erosion Using Linear Spectral Mixture Analysis Of Landsat Etm Data. *Isprs Journal Of Photogrammetry And Remote Sensing, 62*(4), 309-324. Doi: 10.1016/J.Isprsjprs.2007.05.013

Dejong, S. M. (1994). Derivation Of Vegetative Variables From A Landsat Tm Image For Modeling Soil-Erosion. *Earth Surface Processes And Landforms, 19*(2), 165-178. Doi: 10.1002/Esp.3290190207

Haile, M., Herweg, K., & Stillhardt, B. (2006). *Sustainable Land Management A New Approach To Soil And Water Conservation In Ethiopia.*
. University Of Bern, Switzerland: Land Resources Management And Environmental Protection Department Mekelle University, Ethiopia, And Swiss Centre For Development And Environment, National Centre Of Competence In Research (Nccr) North-South University Of Bern, Switzerland.

Herweg, K., & Ludi, E. (1999). The Performance Of Selected Soil And Water Conservation Measures—Case Studies From Ethiopia And Eritrea. *Catena, 36*(1–2), 99-114. Doi: 10.1016/S0341-8162(99)00004-1

Herweg, K., & Ludi, E. (1999). The Performance Of Selected Soil And Water Conservation Measures - Case Studies From Ethiopia And Eritrea. *Catena, 36*(1-2), 99-114. Doi: 10.1016/S0341-8162(99)00004-1

Herweg, K., & Stillhardt, B. (1999). Variability Of Soil Erosion In The High Lands Of Ethiopia And Eritrea. In E. Ministry Of Agriculture (Ed.), *Average And Extreme Erosion Patterns* (Vol. 42, Pp. 81). University Of Berne, Swirzerland: Centre For Development And Environment University Of Berne, Switzerland.

Kaltenrieder, J. (2007). *Adaptation And Validation Of The Universal Soil Loss Equation (Usle) For The Ethiopian-Eritrean Highlands.* Phd Soil Erosion, The Faculty Of Science Faculty University Of Bern, Switherland, University Of Bern.

Kefi, M., Yoshino, K., Setiawan, Y., Zayani, K., & Boufaroua, M. (2011). Assessment Of The Effects Of Vegetation On Soil Erosion Risk By Water: A Case Of Study Of The Batta Watershed In Tunisia. *Environmental Earth Sciences, 64*(3), 707-719. Doi: 10.1007/S12665-010-0891-X

Kheir, R. B., Cerdan, O., & Abdallah, C. (2006). Regional Soil Erosion Risk Mapping In Lebanon. *Geomorphology, 82*(3-4), 347-359. Doi: 10.1016/J.Geomorph.2006.05.012

Lal, R. (2003). *Soil Degradation In The United States: Extent, Severity, And Trends*. Gb: Crc Press Inc.

Meusburger, K., Banninger, D., & Alewell, C. (2010). Estimating Vegetation Parameter For Soil Erosion Assessment In An Alpine Catchment By Means Of Quickbird Imagery. *International Journal Of Applied Earth Observation And Geoinformation, 12*(3), 201-207. Doi: 10.1016/J.Jag.2010.02.009

Mikos, M., Jost, D., & Petkovsek, G. (2006). Rainfall And Runoff Erosivity In The Alpine Climate Of North Slovenia: A Comparison Of Different Estimation Methods. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 51*(1), 115-126. Doi: 10.1623/Hysj.51.1.115

Moa, E. (2002). *The National Action Programme For Eritrea To Combat Desertification And Mitigate The Effects Of Drought (Nap).* Asmara, Eritrea: Ministry Of Agriculture.

Morgan, R. P. C. (2005). *Soil Erosion And Conservation*. Gb: Blackwell Publishing.

Morgan, R. P. C., Morgan, D. D. V., & Finney, H. J. (1984). A Predictive Model For The Assessment Of Soil Erosion Risk. *Journal Of Agricultural Engineering Research, 30*(0), 245-253. Doi: Http://Dx.Doi.Org/10.1016/S0021-8634(84)80025-6

Mutekanga, F. P., Visser, S. M., & Stroosnijder, L. (2010). A Tool For Rapid Assessment Of Erosion Risk To Support Decision-Making And Policy Development At The Ngenge Watershed In Uganda. *Geoderma, 160*(2), 165-174. Doi: 10.1016/J.Geoderma.2010.09.011

Negassi, A., Tengnäs, B., Bein, E., & Gebru, K. (2000). Soil Conservation In Eritrea: Some Case Studies *Regional Land Management Unit (Relma), Swedish International Development Cooperation Agency (Sida).*

Nigel, R., & Rughooputh, S. (2010). Mapping Of Monthly Soil Erosion Risk Of Mainland Mauritius And Its Aggregation With Delineated Basins. *Geomorphology, 114*(3), 101-114. Doi: 10.1016/J.Geomorph.2009.06.013

Nyssen, Poesen, J., Moeyersons, J., Deckers, J., Haile, M., & Lang, A. (2004). Human Impact On The Environment In The Ethiopian And Eritrean Highlands—A State Of The Art. *Earth-Science Reviews, 64*(3–4), 273-320. Doi: 10.1016/S0012-8252(03)00078-3

Nyssen, J., Vandenreyken, H., Poesen, J., Moeyersons, J., Deckers, J., Haile, M., . . . Govers, G. (2005). Rainfall Erosivity And Variability In The Northern Ethiopian Highlands. *Journal Of Hydrology, 311*(1–4), 172-187. Doi: 10.1016/J.Jhydrol.2004.12.016

Ogbazghi, W., Stillhardt, B., & Herweg, K. (2011). *Sustainable Land Management A Textbook With A Focus On Eritrea.* Varicolor, Switzerland: Geographica Bernensia Bern And Hamelmalo Agricultural College.

Renard, K. G., & Freimund, J. R. (1994). Using Monthly Precipitation Data To Estimate The R-Factor In The Revised Usle. *Journal Of Hydrology, 157*(1-4), 287-306. Doi: 10.1016/0022-1694(94)90110-4

Salako, F. K. (2006). Rainfall Temporal Variability And Erosivity In Subhumid And Humid Zones Of Southern Nigeria. *Land Degradation & Development, 17*(5), 541-555. Doi: 10.1002/Ldr.738

Semere, Z. (2002). *Assessment Of Soil And Water Conservation Activities In Afdeyu, Eritrea Technical And Socio-Economic Aspects.* Msc, Wageningen University, Department Of Soil And Water Conservation, Wageningen, Netherlands, The Publication Of This Msc Thesis Was Funded By The Sustainable Land Management Programme (Slm) Eritrea, Which Is Financed By Syngenta Foundation For Sustainable Agriculture, Basle, Switzerland. (3-906151-65-4)

Shiferaw, A. (2011). Estimating Soil Loss Rates For Soil Conservation Planning In The Borena Woreda Of South Wollo Highlands, Ethiopia. . *Journal Of Sustainable Development In Africa, Volume 13,*, 106.

Stillhardt, B., Herweg, K., & Hurni, H. (2002). *Long-Term Monitoring Of Soil Erosion And Soil And Water Conservation In Afdeyu, Eritrea (1984 –1998)* Centre For Development And Environment (Cde), University Of Berne, Switzerland
Syngenta Foundation For Sustainable Agriculture, Switzerland.

Symeonakis, E., & Drake, N. (2004). Monitoring Desertification And Land Degradation Over Sub-Saharan Africa. *International Journal Of Remote Sensing, 25*(3), 573-592. Doi: 10.1080/0143116031000095998

Symeonakis, E., & Drake, N. (2010). 10-Daily Soil Erosion Modelling Over Sub-Saharan Africa. *Environmental Monitoring And Assessment, 161*(1-4), 369-387. Doi: 10.1007/S10661-009-0754-7

Tesfahunegn, G. B., Vlek, P. L. G., & Tamene, L. (2012). Management Strategies For Reducing Soil Degradation Through Modeling In A Gis Environment In Northern Ethiopia Catchment. *Nutrient Cycling In Agroecosystems, 92*(3), 255-272. Doi: 10.1007/S10705-012-9488-Y

Tesfai, M., & Sterk, G. (2002). Sedimentation Rate On Spate Irrigated Fields In Sheeb Area, Eastern Eritrea. *Journal Of Arid Environments, 50*(1), 191-203. Doi: 10.1006/Jare.2001.0862

Tesfamicael, B. A. (2005). *Poverty And Natural Resource Management In The Central Highlands Of Eritrea.* Doctorate (Phd) Phd, University Of Groningen, University Of Groningen.

Van Der Knijff, J. M. J., R.J.A.; Montanarella, L. (2000). Soil Erosion Risk Assessment In Europe. [European Commision Directorate General Jrc Joint Research Centre Space Applications Institute European Soil Bureau]. *European Commision Soil Bureau, Eur 19044 En.*

Van Dijk, A., Bruijnzeel, L. A., & Rosewell, C. J. (2002). Rainfall Intensity-Kinetic Energy Relationships: A Critical Literature Appraisal. *Journal Of Hydrology, 261*(1-4), 1-23. Doi: 10.1016/S0022-1694(02)00020-3

Vemu, S., & Pinnamaneni, U. B. (2011). Estimation Of Spatial Patterns Of Soil Erosion Using Remote Sensing And Gis: A Case Study Of Indravati Catchment. *Natural Hazards, 59*(3), 1299-1315. Doi: 10.1007/S11069-011-9832-6

Vrieling, A. (2006). Satellite Remote Sensing For Water Erosion Assessment: A Review. *Catena, 65*(1), 2-18. Doi: 10.1016/J.Catena.2005.10.005

Vrieling, A., De Jong, S. M., Sterk, G., & Rodrigues, S. C. (2008). Timing Of Erosion And Satellite Data: A Multi-Resolution Approach To Soil Erosion Risk Mapping. *International Journal Of Applied Earth Observation And Geoinformation, 10*(3), 267-281. Doi: 10.1016/J.Jag.2007.10.009

Vrieling, A., Sterk, G., & De Jong, S. M. (2010). Satellite-Based Estimation Of Rainfall Erosivity For Africa. *Journal Of Hydrology, 395*(3-4), 235-241. Doi: 10.1016/J.Jhydrol.2010.10.035

Vrieling, A., Sterk, G., & Vigiak, O. (2006). Spatial Evaluation Of Soil Erosion Risk In The West Usambara Mountains, Tanzania. *Land Degradation & Development, 17*(3), 301-319. Doi: 10.1002/Ldr.711

Wang, G. Q., Hapuarachchi, P., Ishidaira, H., Kiem, A. S., & Takeuchi, K. (2009). Estimation Of Soil Erosion And Sediment Yield During Individual Rainstorms At Catchment Scale. *Water Resources Management, 23*(8), 1447-1465. Doi: 10.1007/S11269-008-9335-8

Wischmeier, H. W., & Smith, D. D. (1978). *Predicting- Rainfall Erosion Losses: A Guide To Conservation Planning* United States Department Of Agriculture: Science And Education Administration.

Yuksel, A., Gundogan, R., & Akay, A. E. (2008). Using The Remote Sensing And Gis Technology For Erosion Risk Mapping Of Kartalkaya Dam Watershed In Kahramanmaras, Turkey. *Sensors, 8*(8), 4851-4865. Doi: 10.3390/S8084851

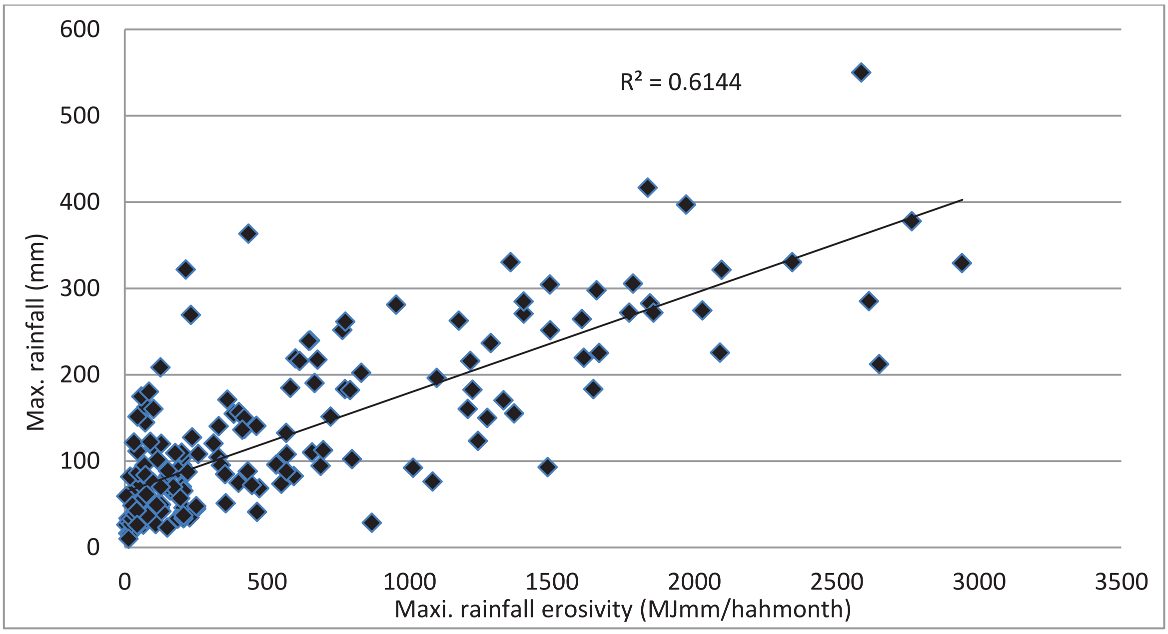
Zachar, D. (1982). *Soil Erosion: Developments In Soil Science 10*. Us: Elsevier Science.

Zhang, X. W., Wu, B. F., Li, X. S., & Lu, S. L. (2012). Soil Erosion Risk And Its Spatial Pattern In Upstream Area Of Guanting Reservoir. *Environmental Earth Sciences, 65*(1), 221-229. Doi: 10.1007/S12665-011-1085-X

Appendexes

Appendix I: Rainfall erosivity and its spatio-temporal Variability

Assessment of maximum rainfall (mm) and maximum erosivity (MJmm/hahmonth) derived from TRMM-3B43 and TRMM-3B42 datasets respectively (1998 to 2012) for all pixels.



Appendix II: C –factor estimation

Ground data C-factor estimation on the Eritrean and Ethiopian highlands based on the literatures of Kaltenrieder (2007).

Type of crops	C-factor
Dense forest	0.001
Other forest	0.05
Bad lands hard	0.05
Bad lands soft	0.4
Sorghum, Maize	0.1
Cereals, Pulses	0.15
Dense grass	0.01
Degraded grass	0.05
Fallow hard	0.05
Fallow ploughed	0.6
Ethiopian tef	0.25
Continuous fallow (bare lands)	1.0

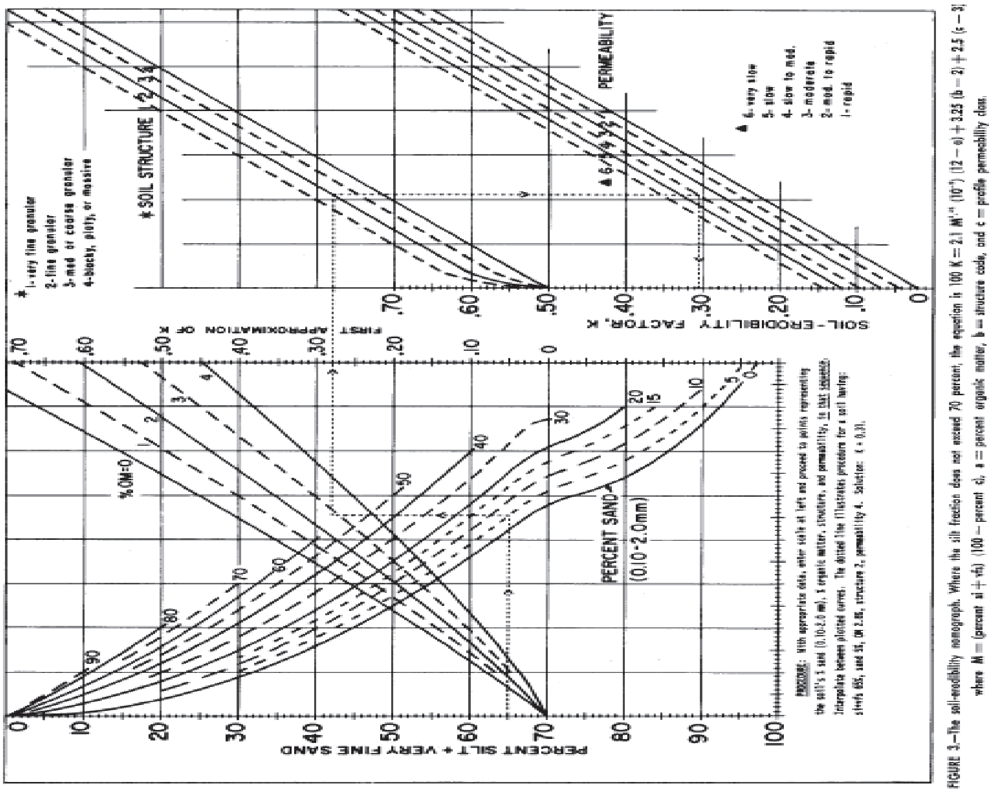
Appendix III: common soil units with its properties for the study area

The soil properties for the study area were generated from FAO Harmonized Soil map of the World. The website is (http://www.fao.org/nr/aboutnr/nrl/en/).

FAO Common Soil Units in Eritrea	K-factor	Soil unit symbol	sand % topsoil	sand % subsoil	silt % topsoil	silt% subsoil	clay % topsoil	clay % subsoil	pH water topsoil	pH water subsoil	OC % topsoil	OC % subsoil	N % topsoil	N % subsoil	BS % topsoil	BS % subsoil	CEC topsoil	CEC subsoil	CEC clay topsoil	CEC Clay subsoil	CaCO3 % topsoil	CaCO3 % subsoil
Orthic Acrisols	0.27	AO	53.6	43.4	15.8	16	30.6	40.6	5.1	5.2	2.25	0.75	0.18	0.07	39	32	7.6	7.5	35	23	0	0
Dystric Cambisols	0.33	BD	32.7	29.8	30.3	37.6	37.1	32.3	4.9	5.3	3.28	0.87	0.23	0.05	16	20	19.1	14.1	53	39	0	0
Humic Cambisols	0.45	BH	55.2	60.4	21	16.5	23.8	23.2	5.3	5.8	3.86	1.78	0.47	0.21	38	39	17.9	12.9	50	48	0	0
Lithosols	0.35	I	58.9	56	16.2	17	24.9	27	7.1	7.2	0.97	0.4	0.13	0.02	69	90	10.4	8	55	28	0.1	0.5
Eutric Nitosols	0.25	NE	68.4	57.8	10.5	10	21.2	32.2	6.3	6.5	0.6	0.32	0.18	0.07	75	77	8.8	11.1	41	39	0	0.1
Cambisols	0.28	Q	91.9	91.8	3.2	3	5	5.4	6.2	6.3	0.23	0.13	1.31	0.02	75	71	3.5	3	51	49	0.1	0.1
Calcaric regosols	0.35	RC	63.5	62.8	19.2	18.4	17.3	18.7	7.6	7.6	0.76	0.41	0.28	0.04	89	89	10.7	11.2	52	50	15.1	1.9
Eutric Gleysols	0.37	RE	68.3	71.6	15.1	15.2	16.6	13.2	6.4	6.8	0.5	0.45	0.06	0.06	83	76	10.2	6.7	44	42	1.6	6.4
Solonetz	0.25	S	55.4	47.3	20.4	19.8	24.2	32.8	8.2	8.6	0.65	0.48	0.11	0.05	95	92	14.7	18.7	55	51	1.3	4.7
Chromic vertisols	0.15	VC	22.4	20.8	24.5	23.5	53	55.7	7.8	8	0.69	0.46	0.08	0.06	98	99	45.3	44.8	82	80	3.8	6
Haplic xerosols	0.23	XH	54.8	52.4	20.6	21.5	24.9	26.3	7.7	8.2	0.53	0.24	0.09	0.06	99	100	17.5	15.2	66	71	0.8	1.7
Luvic xerosols	0.3	Xl	76	70.8	8	8.4	16.1	20.9	7.1	7.3	0.32	0.24	0.03	0.03	86	86	12.7	14	50	46	1.1	2.2
Yermosols/Fluvisols	0.2	Y	49.2	42.4	26	27.9	24.8	29.3	7.7	7.8	0.33	0.23	0.1	0.06	96	96	8.7	7.9	66	50	13.1	22.1

Appendix IV: Erodibility estimation using Nomograph

K-factor estimation using Wischmeier and Smith (1978) nomograph.



Appendix-VI: Mean multi-seasonal rainfall, erosivity, runoff and soil loss for Afdeyu (1985-2002), Source (Stillhardt et al., 2002)

Month	Rainfall [mm]	Erosivity [J/mh]	Test plot 1, slope: 31 %, grass		Test plot 2, slope: 2 %, annual crops		Test plot 3, slope: 10 %, annual crops		Test plot 4, slope: 65 %, rocks, grass	
			Runoff (mm)	Soil loss (t/ha)	Runoff (mm)	Soil loss (t/ha)	Runoff (mm)	Soil loss (t/ha)	Runoff (mm)	Soil loss (t/ha)
Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	5.4	0.7	0.3	0.0	0.0	0.0	0.5	0.0	0.1	0.0
Apr	28.2	14.5	0.8	0.2	1.3	0.3	1.5	0.2	1.1	0.2
May	44.9	26.0	7.1	0.1	2.6	0.1	10.4	1.0	7.3	0.7
Jun	22.6	6.9	7.5	0.4	11.5	1.2	9.9	1.3	5.5	0.8
Jul	107.7	57.0	22.9	2.7	26.2	5.1	24.4	2.0	14.5	1.9
Aug	148.4	116.5	74.4	6.8	101.1	7.8	82.9	8.3	65.1	6.0
Sep	59.4	52.5	36.2	2.6	31.3	1.8	31.8	1.8	27.1	2.6
Oct	28.5	12.8	5.5	0.6	1.3	0.1	5.2	0.4	5.6	1.2
Nov	12.0	4.0	2.6	0.1	0.4	0.0	2.0	0.0	1.5	0.3
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0