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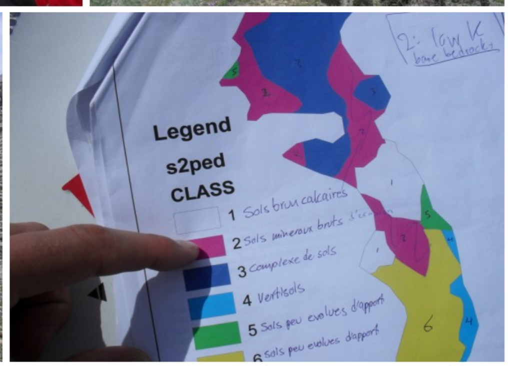
Soil Loss Estimation Based on the USLE/GIS Approach Through Small Catchments

- A Minor Field Study in Tunisia



Linus Andersson

Division of Water Resources Engineering
Department of Building and Environmental Technology
Lund University

Avdelningen för Teknisk Vattenresurslära

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Abstract

A USLE/GIS approach was applied to estimate soil loss for the two catchments 'Mrichet' and 'Sadine2' in the semi-arid Tunisian Dorsal. The approach is inspired by the doctoral thesis 'Water erosion modeling using fractal rainfall disaggregation – A study in semiarid Tunisia' by Dr. Sihem Jebari. The Universal Soil Loss Equation (USLE) was applied to predict soil loss magnitude and Geographic Information System (GIS) software *ArcView* and *ArcMap* was used to simulate the soil loss in spatial distribution. Each one of the USLE-parameters (rainfall erosivity R, soil Erodibility K, topography LS, conservation practice P and land use C) were represented by a thematic raster layer in the GIS. The thematic layers were defined from available data such as satellite images (C and P), pedological maps (K), rainfall intensity records (R) and topographic maps (LS). The model was calibrated primarily considering the grid cell size resolution of the raster layers. The estimated soil loss was, depending on the grid cell dimension used, estimated at approximately 12-16% of the observed soil loss for both catchments. The underestimation of the soil loss is most likely due to underestimated K- and R-factor values. Also the USLE is restricted to rill and inter rill erosion while the comparative observed erosion is likely to include all types of water erosion within the catchment. This implies that the modeled values could be expected lower than the observed. In addition some soil samples were analyzed and K-factor values experimentally determined for comparison with the theoretical. These values were in the same order of magnitude as the theoretically determined.

Keywords; USLE, Universal Soil Loss Equation, GIS, soil loss, erosion, water erosion modeling, Tunisia, MFS, Minor Field Study

LUNDS TEKNISKA HÖGSKOLA
Lunds universitet

Lund University
Faculty of Engineering, LTH
Departments of Earth and Water Engineering

This study has been carried out within the framework of the Minor Field Studies (MFS) Scholarship Programme, which is funded by the Swedish International Development Cooperation Agency, Sida.

The MFS Scholarship Programme offers Swedish university students an opportunity to carry out two months' field work in a developing country resulting in a graduation thesis work, a Master's dissertation or a similar in-depth study. These studies are primarily conducted within subject areas that are important from an international development perspective and in a country supported by Swedish international development assistance.

The main purpose of the MFS Programme is to enhance Swedish university students' knowledge and understanding of developing countries and their problems. An MFS should provide the student with initial experience of conditions in such a country. A further purpose is to widen the human resource base for recruitment into international co-operation. Further information can be reached at the following internet address: http://www.tg.lth.se/mfs.

The responsibility for the accuracy of the information presented in this MFS report rests entirely with the authors and their supervisors.

Gerhard Barmen
Local MFS Programme Officer

Preface

This project is part of my Master of Science degree in *Environmental Engineering / Water Resource Management* at the Division of Water Resource Engineering (TVRL, LTH/Lund University). The project is a combination of a literature review in the field of work and a simulation in soil loss estimation for two smaller catchments in semiarid Tunisia. In addition to this also some field experiments are included. Most of the literature review of this project is performed at Lund's University, Sweden, while the modeling phase (including construction of the model, field work and calibration)and the field work is performed at the INRGREF (Tunisian National Research Institute for Rural Engineering, Water and Forestry) research institute in Tunis, Tunisia. The study is supported by the Minor Field Study scholarship from Swedish aid organization SIDA and is inspired by the doctoral thesis 'Water erosion modeling using fractal rainfall disaggregation – A study in semiarid Tunisia' by Dr. Sihem Jebari at INRGREF, Tunis, Tunisia, who also suggested the subject.

Supervisor for this project is Professor Ronny Berndtsson at TVRL, LTH / Lund University. Examiner is Professor Kenneth M. Persson at TVRL, LTH/Lund University. The model work in Tunisia is supervised and guided by Dr. Sihem Jebari at INRGREF, Tunis, Tunisia. Opponents are Kalle Koinberg and Patrik Gliveson.

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Finally a special thanks to the Jebari family (Omar, Walid) and Bouksila Fethi with family for taking care of me during my stay. I would also like to mention coach Imed, coach Zied, Monsieur Trabelsi and all the others at *Federation de Boxe Tunisienne*.

Soil Loss Estimation Based on the USLE/GIS Approach Through Small Catchments

1. Introduction

1.1. Background

In Africa it is estimated that the decrease in productivity due to soil erosion is 2-40% with an average of 8.2% for the whole continent (Eswaran et al, 2001). Also an average of 19% of the reservoir storage volumes of Africa are silted (Jebari et al, 2009). In Tunisia in particular the problem is severe and has been present for a long time with indications of measures taken against erosion thousands of years ago by the Romans (Jebari 2009, FAO 1990, Toy et al 2002).

Every year 15 000 hectares of farming land is lost due to the erosion processes, affecting as much as 20% of the total land area of the country (Jebari, 2009). In a recent report concerning erosion and siltation in Tunisia Jebari et al (2010) states that in the Tunisian Dorsal (the eastern parts of the Atlas Mountains where the sites of this study are located) 7% of the land area is badly damaged by erosion and as much as 70% moderately damaged, leaving only 28% of the Dorsal soil cover left. The situation is an effect of thousands of years of agricultural activity in the area, but also to some extent short term effects from dams built in the 60s and 70s have influenced the degradation. The main contribution of the degradation is however the Mediterranean climate and conditions. The erosion effects are amplified by the region soil structure being less developed; immature soils of rock origin with low organic content. The high rates of weathering and erosion processes prevent soils from reaching maturity. Also infiltration of water is decreased by shallow calcareous crust formations due to high evaporation rates (Jebari et al, 2010) which in its turn accelerates the erosion processes.

The water demand in the Mediterranean region is now not far from the available resources and water is becoming more expensive and more of a weight on the economy (Jebari et al, 2010). This obviously also has a negative impact on the agricultural productivity, causing economical losses. It is therefore of great importance to map these processes in order launch measures to control them. This project origins from the doctoral thesis of Dr. Sihem Jebari, present at agricultural research institute INRGREF, Tunis, Tunisia; 'Water erosion modeling using fractal rainfall disaggregation – A study in semiarid Tunisia' (Jebari, 2009).

'Water erosion modeling using fractal rainfall disaggregation – A study in semiarid Tunisia' includes the construction of a model that simulates the magnitude of soil loss in spatial distribution. Jebari states that the main objective of her thesis is to develop a methodology for prediction of siltation (Jebari, 2009). This method used is called the USLE/GIS approach, which utilizes the empirical equation *Universal Soil Loss Equation* (USLE) integrated in *Geographic Information System* (GIS) software. In her thesis, the rainfall disaggregation for determination of the rainfall erosivity factor is the main focus.

1.2. Purpose

This project will give more focus on the general USLE/GIS approach for semiarid conditions, treating a full construction of the model. The model will be derived from available data such as soil maps, topographic maps, rainfall records, land use maps and satellite images. Finally the model is calibrated and confirmed with siltation records observed in the modeled catchments. In addition, also some field work will be performed to make comparisons with the theoretical values of soil properties.

The USLE/GIS-approach aims to generate a spatial distribution map describing the soil loss of the two study sites. Interpretation of such a map will supposedly give the information required to take measures to prevent potential erosion. However the main purpose of this project is oriented to applications of the USLE/GIS approach for semiarid conditions in terms of methodology and calibration. Several similar student projects are performed parallel at INRGREF under the supervision of Dr. Jebari; together the results and conclusions of these will contribute to the development of erosion prediction technology for semiarid conditions, where it is needed the most. In addition to the model work, this paper also contains a literature review performed in the approach and in related processes in order to provide the reader a basic introduction in the field and to understand the approach as it is used today.

2. Literature Review

2.1. Soil Erosion Processes

Earth landscape processes such as soil erosion and deposition have been active since the first rain fell and the first wind blew millions of years ago, playing a significant role in the formation of these landscapes (Toy et al, 2002). To understand the processes of erosion, it is also relevant to see it in its context. Erosion processes are driven by the potential energy generated from tectonic activities inducing the landscape cycle, raising and lowering the surface of the earth. The degradation of the landscape works through four types of external processes: rock weathering, mass movement, erosion and deposition (Toy et al, 2002). This chapter will treat a brief introduction on the basic functions of soil erosion processes.

2.1.1. Soil Formation

Soil can be described as the earth surface top layer persisting of both mineral and organic material (Strahler & Strahler, 2003). The structure and consistency of soils can vary widely. The mineral matter of soils is the product of rock-weathering processes, while the organic matter content origins from decomposition of biological matter (Strahler & Strahler, 2003). There are mainly two types of rock-weathering processes; physical weathering and chemical weathering (Toy et al, 2002). Physical weathering is decomposition of rocks into smaller fractures through various physical or mechanical processes (Strahler & Strahler, 2003). The chemical weathering process is degradation of rocks due to changes and decomposition in the mineral content (Toy et al, 2002). Examples of chemical weathering processes are acid reactions, hydrolysis and oxidation reactions (Strahler & Strahler, 2003).

2.1.2. *The Water Erosion Process*

The type of erosion is generally classified by the erosive agent inducing the process; wind or water (Toy et al, 2002). Water erosion can occur in many ways, for example coastal erosion by waves, splash erosion from the impact of precipitation and irrigation water, erosion due to overland flow (also called sheet erosion or rill/inter-rill erosion), stream channel erosion or erosion by percolating water (Strahler & Strahler, 2003). Basically the impact of water droplets and/or the sheer stress caused by water in motion detaches soil particles, followed by transport and finally deposition of the particles eroded (Strahler & Strahler, 2003).

During storm events, rainfall intensity can exceed the infiltration capacity of the soil and the excess water will form a runoff directed downslope (Toy et al, 2002). The magnitude of the runoff varies due to different factors such as the initial soil moist, the infiltration capacity and the variations in precipitation intensity (Toy et al, 2002). The moving water in the runoff and sub-surface flow naturally induces erosion on the soil. The runoff will cause sheet erosion, which is more or less spatially uniform removal of soil, or rill erosion which occurs in small closely related channels called rills (Strahler & Strahler, 2003; Toy et al, 2002). With time rill erosion will progress to gully erosion as the channel increases in size and is defined as a gully (Toy et al, 2002).

2.1.3. Soil erodibility

Many factors are important for the soils ability to resist erosion. The permeability is important since it defines how the precipitation will be divided in terms of soil moisture, surface runoff and infiltrated ground water (Toy et al, 2002). Also organic content is important; a higher organic content will decrease the soil erodibility (FAO, 1996). As a high organic content increases the porosity and thereby also the permeability and the water holding capacity of the soil, potential erosive runoff is reduced (Jankauskas et al, 2007). High presence of coarse grain size particles also reduces the erosion significantly. For example in Mediterranean calcareous soils like the soils of semiarid Tunisia, a 10% presence of pebbles in the surface horizon reduces the erodibility by as much as 15%, why a high content of pebbles indicates good resistance to erosion (FAO, 1996). As seen in the 'Hjulström diagram' in *Figure 1*, the grain size of approximately 1-300 microns, which is for fine and medium sand, have the highest tendency to erode. If the grain size is smaller the cohesive forces between the grains will prevent detachment, while larger grains are too heavy to transport (FAO 1996). *Figure 1* also displays how the water velocity affects the erosion.

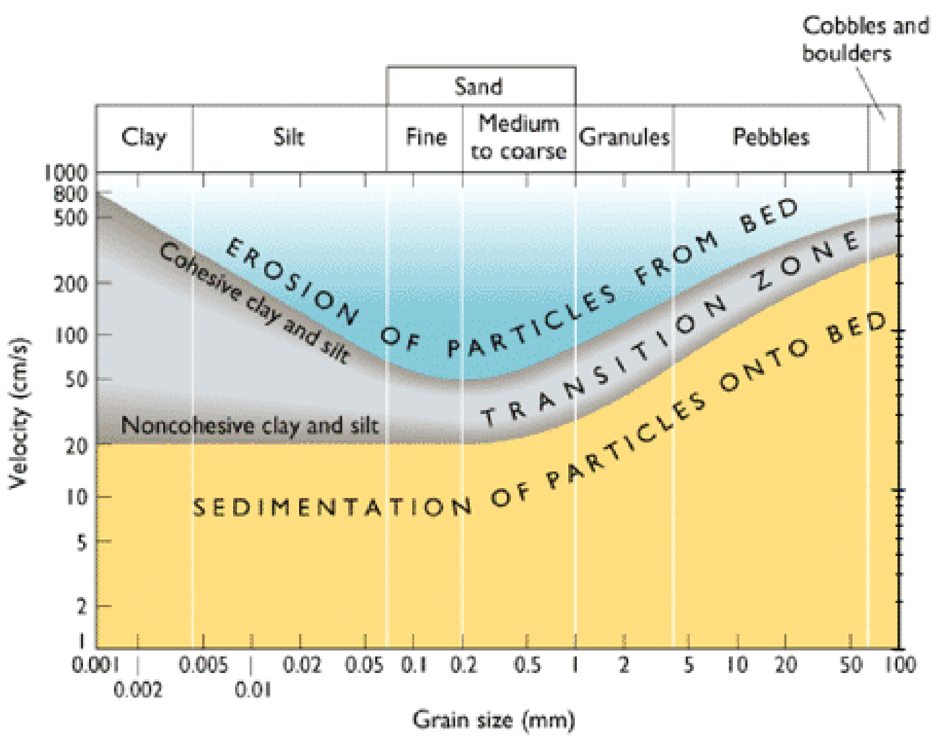


Figure 1; *Hjulström diagram, the grain size most sensitive to erosion is about 0.1mm (Columbia University, 2008)*

2.1.4. The Drainage Basin

A good way to analyze water erosion spatially is in the context of a drainage basin (watershed, catchment), ranging in size from a few acres or less up to thousands of acres (Toy et al, 2002) or even thousands of square kilometers (Beskow et al, 2009) for large river basins. As seen in *Figure 2*, the boundary of a drainage basin is defined by the landscape topography, directing the input water. A drainage basin can be regarded as a hydrological unit contributing to a river (or a reservoir), where the input (precipitation) is equal to the output (evaporation and stream flow) with regards to the changes in storage (Ward & Robinson, 2000). The flow of water in a drainage basin, oriented towards the "output river", can occur either as open channel flow in rills, gullies and stream channels, or as sub-surface flow in the soil macro-pores (Toy et al, 2002).

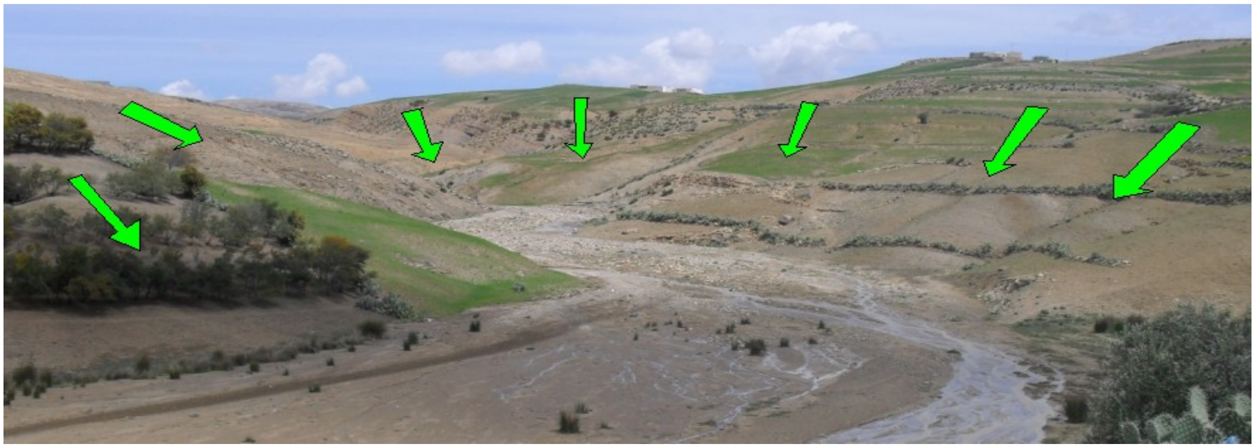


Figure 2; ***The topography directs the precipitation and thereby defines the catchment borders.***

2.1.5. Topography

Besides form defining the drainage basin limit, topography is a major factor influencing soil erosion potential. Related to erosion processes, topography is described in terms of slope length (distance) and slope steepness (ratio) and can be uniform (constant over the length), convex (increasing slope), concave (decreasing slope) or a complex of these (Toy et al, 2002).

2.2. Soil Erosion Related Problems

Erosion act on land and inhabitants in many ways by changing the soil properties, bringing both economical and social consequences on populations. Erosion related economical consequences in local, regional and national scales can be derived from physical and chemical changes in the soil properties, causing reductions in crop yields and requirements of increased efforts to maintain the agricultural productivity (Toy et al, 2002). These problems are related to the changes in water holding capacity, nutrient availability, reduction of organic matter content and general soil degradation (Toy et al, 2002).

Also siltation decreasing the water reservoir capacity is a great problem (*Figure 3*), especially in the Mediterranean river basin (Jebari et al, 2010). A decreased reservoir also means less water for irrigation and food supply as well as reductions in flood control. It has proven to be problematic to directly map the relation of erosion to agricultural productivity due to the spatial and temporal variations of involved conditions, but according to Toy et al (2002) erosion definitely affects this productivity in both short and long term.

Figure 3; ***Silted reservoir in 'Sadine2' catchment in the Tunisian Dorsal. The reservoir has a capacity of 108 800 m^3 and was almost completely silted in approximately 10 years.***

2.2.1. Erosion and Sediment Control

Sediment delivery can be reduced by reducing the waters sediment transport capacity, which in its turn is reduced by a lower water velocity. But as seen in the 'Hjulström diagram' (*Figure 1*) this will primarily cause a deposition of coarse grained particles, which reduces the pollution potential in the runoff less than it reduces the total delivery of sediments, all because the fine sediments cause a more extensive degradation of water quality and can also carry adsorbed pollutants like chemicals (Toy et al, 2002). Therefore the best way to apply water and soil conservation practices is to protect the soil by reducing detachment – only reducing the water sediment transport capacity will just cause a selection of eroded particles; coarse particles will be left behind in the soil and pollution will be retained in the runoff (Toy et al, 2002).

Toy et al (2002) describes some basic concepts for erosion-control principles. Some important conservation practices are listed below;

- Maintain vegetation/ground cover; erosion is reduced by the ground cover providing canopy that intercepts the rainfall and thereby reduces its erosivity. Ground cover from plant litter also contributes and root networks improves soil fixation. Plant litter is preferably maintained for the period of highest rainfall erosivity (if not possible for the whole year).

- Add support practices such as banquettes, terraces, vegetation strips, strings of rock and armored waterways to reduce erosion in steep slopes. Ridging or contouring perpendicular to the runoff is also a good measure.

- Modify the topography to avoid convexity at the end of slopes. Flat and concave segments at the end of a slope are preferred to induce deposition.

- Incorporate biomass (manure, sewage sludge, paper mill waste) into the soil; as mentioned in *2.1.3 Soil Erodibility,* the erodibility is reduced with increased organic matter content in the soil. Also the litter of last year's crop will contribute to higher organic matter content.

- Crop rotation – if a crop is sensitive to erosion it can be cultivated in rotation with another crop with less erosive attributes to improve the overall influence.

Figure 4; *´String of rock´ conservation measure by the Tunisian Ministry of Water and Soil Conservation. The landowner improves the ridge by planting cactuses to consolidate the structure.*

An example of conservation measures in semiarid Tunisia is these stone ridges (*Figure 4*). Initially a string of rock is founded by the Tunisian Ministry of Water and Soil Conservation. Then the landowner continues the work by consolidating the structure with soil and adding pieces of cactus, intended to root (*Figure 4A*). Eventually the cactuses will grow and form a vegetated rock strip, consolidated with cactus roots and deposited soil, effectively stopping the runoff and eroded sediments can be deposited (*Figure 4B*).

2.3. Universal Soil Loss Equation (USLE)

The simplest mathematical model for prediction of soil loss is the *Universal Soil Loss Equation* (USLE) and has been frequently used over the world since it was developed by American statistician W. H. Whichmeier in the 1960s (Fistikogli & Harmancioglu 2002, USDA/NSERL 2010). The model is empirical and was developed using over 10,000 statistical records of erosion, sampled over the American Great Plains (FAO 1996). In fact the USLE is the most widely used equation in erosion modeling (Fistikogli & Harmancioglu 2002).

The USLE describes average annual soil loss rates based on estimated and measured input data. The input data is divided into five different factors; *rainfall erosivity, soil erodibility, topography, crop management* and *conservation practice*. The factors of the USLE vary over different storm events but tend to average out over long-term conditions, why the equation is applicable in these actual conditions (Fistikogli & Harmancioglu 2002).

2.3.1. Equation Parameters

The annual soil loss *A* from the USLE (*eq.1*) is a mathematical product of the input parameters shown in *Table 1*, given in ton per hectare and year.

$$A = R \cdot K \cdot LS \cdot C \cdot P \qquad (eq.1)$$

Table 1; *The USLE input factors with units where 'MJ' is megajoule, 'mm' millimeters, 'ha' hectares, 'h' hours, 'yr' years and 't' tons (Beskow et al, 2009).*

Parameter	**Unit**
R=rainfall erosivity factor	$\frac{MJ \cdot mm}{ha \cdot h \cdot yr}$
K=soil erodibility factor	$\frac{t \cdot h}{MJ \cdot mm}$
LS= topographical factor (length, slope)	-
C=crop management factor	-
P=conservation practice factor	-

2.3.1.1. Rainfall Erosivity Factor (R)

The contribution of the erosive agent water (precipitation) is represented by the rainfall erosivity factor *R*. This factor is may be the most important factor in the USLE compared to the other input parameters (Jebari, 2009). The kinetic energy of the rain can be considered as the potential rainfall energy available to be transformed into erosion. The erosivity of a single raindrop is naturally described as the droplet kinetic energy *E*; the mass of the droplet multiplied by the square of the velocity at impact divided by two; $E=mV^2/2$ (Toy et al, 2002). The R-factor corresponds to this kinetic energy *E* of the rainfall, multiplied by the maximum intensity of a 30-min rain I_{30} according to the original approach by Whichmeier (FAO, 1996), however Jebari et al (2008) found that using 15-min periods for the maximum rainfall intensities could be more suiting for semiarid regions. The R-factor is calculated over long term conditions (20 years) for all storm events with a precipitation exceeding 12,7 mm. Then an annual average is deduced from this (FAO, 1996). According to the original approach by Whichmeier two valid storm events must be separated by a minimum of six hours (OMM/WCP, 1983). An extensive example of

R-factor determination according to the Whichmeier methodology for a single event is found in *Appendix A*.

2.3.1.2. Soil Erodibility Factor (K)

The soil erodibility factor can be described as the soils tendency to erode. It is dependent on the local soil properties and can be determined in various ways; through sample analysis of the soil, from a soil map or pedological survey of the site or through a combination of these (Jebari, 2009; Fistikogli & Harmancioglu, 2002). Two energy sources are considered to erode the soil and the erodibility factor is defined by the soil ability to resist these sources; the surface impact of the rain droplets and the shearing stress of the horizontal runoff (FAO 1996). Whichmeier determined the main attributes for the soil erodibility factor with experimental plots with both simulated and natural rain under specific conditions; 22 meter plot length, 9% plot slope, no organic matter ploughed in for three years and cultivation of the plot in the direction of slope (FAO, 1996). Whichmeier found that the main attributes of the soil for determining the K-values were organic matter content, texture, surface horizon structure and the permeability.

When determining the K-factor by sample analysis the following data is determined (Roose, 1989);

- The percentage of silt and fine sands; grain sizes 0.002 mm – 0.100 mm
- The percentage of sands; grain sizes 0.100 mm – 2 mm
- The percentage of organic matter content
- The soil structure class where the aggregate durability is considered; 4 classes are used
- The soil permeability class; 6 classes are used

Then the diagram of *Figure 5* is used to deduce the K-factor value in US-units. In the example shown below the sample contains 65% silt and fine sand, 5% sand, 2.8% organic matter content, class 2 in soil structure and class 4 in permeability. The K-value is determined to 0.31, which can be converted to SI-units by conversion factor $K_{SI} = 0.1317K_{US}$ (Zante et al, 2001).

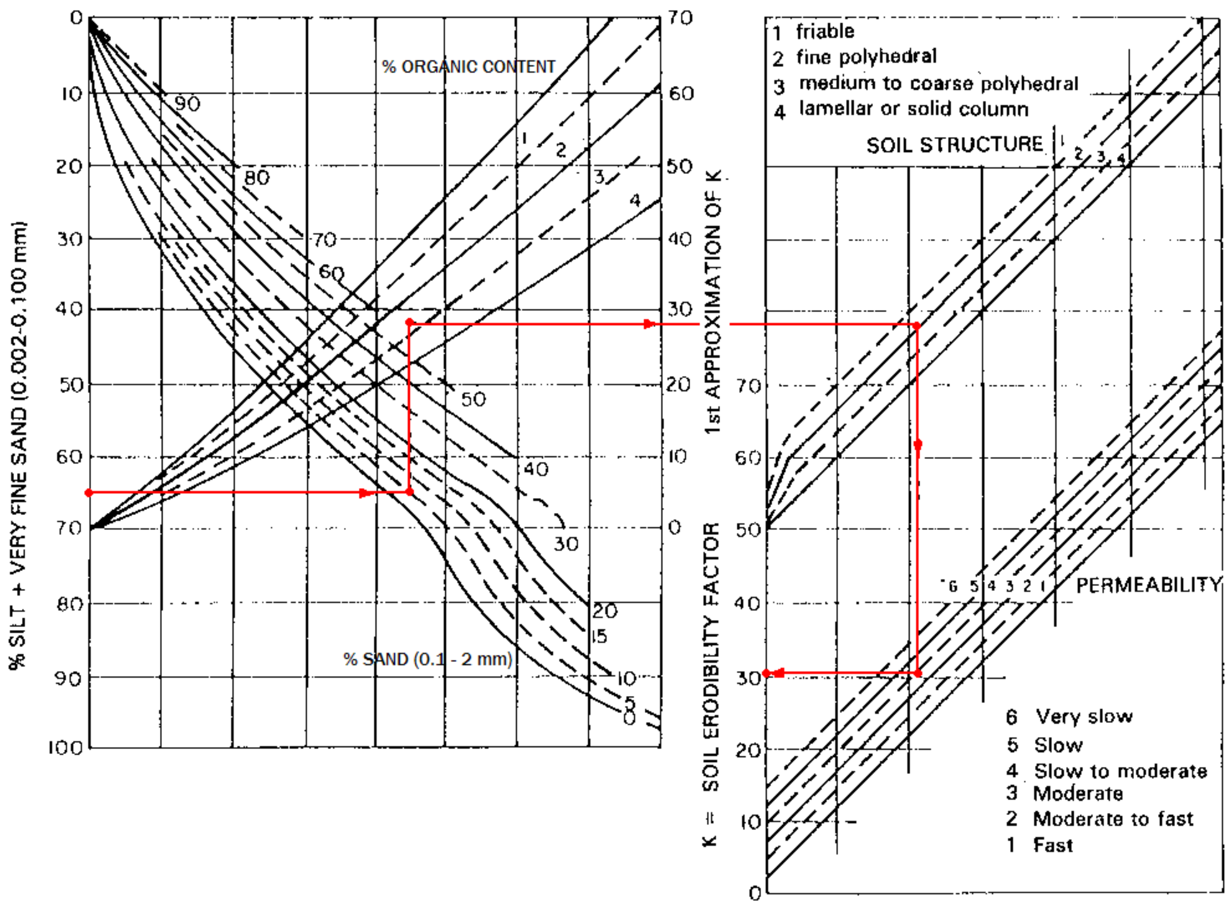


Figure 5; Determination of K-factor value from soil sample analysis (FAO, 1996b).

2.3.1.3. Topographic Factor (LS)

Slope gradient and slope length are normally combined into one single factor in the USLE. This factor can be calculated in various ways depending on unit preferences and other conditions like available data. Different empirical relations are used to determine this factor and many recent studies (Jebari, 2009; Onyando et al, 2004) use the equation (*eq. 2*) recommended by Morgan and Davidson (1991) where *L* is the slope length in meters and *S* is the slope steepness in percent.

$$LS = \sqrt{\frac{L}{22}}\left[\left(0.065 + 0.045S\right) + \left(0.0065 \cdot S^2\right)\right] \qquad (eq.\ 2)$$

Another common method also found in recent articles (Jain et al, 2010; Beskow et al, 2009; Erdogan et al, 2006) is the theoretical relations of the *unit stream power theory* (*eq. 3*) (Moore et al, 1986a, 1986b, 1992) where A_S is the upslope contributing area (taking accumulated flow of sediment and water into consideration) and β is the slope in degrees.

$$LS = \left[\frac{A_S}{22.13}\right]^{0.4}\left[\frac{\sin\beta}{0.0896}\right]^{1.3} \qquad (eq.\ 3)$$

2.3.1.4. Crop Management (C) and Conservation Practice (P) Factors

The C-factor describes the relation between the erosion on bare soil and the erosion on cropped conditions. It is also called the 'plant cover factor' (FAO, 1996). In theory it will adopt a value of 1 for completely unprotected, bare soil (which means no influence on gross erosion estimation) and for more erosion reducing plant cover the value decreases, giving a lower estimation on gross erosion (FAO, 1996). For example an area with light forest vegetation will be assigned a value of 0.10 (Zante et al, 2001).

The P-factor represents erosion reducing measures like terraces or ridging/contouring. The P-factor is assigned the value of 1 when no influences from conservation practices are considered. If conservation measures are taken the value will decrease and thereby lower the estimated erosion (FAO, 1996). For example a banquette on a 5-10% slope will give a P-factor value of 0.10 (Zante et al, 2001).

2.3.2. Limitations

Being the most widely used equation in erosion prediction, the USLE still has limitations and weaknesses;

- The USLE in its original form does not model erosion in a spatial context; however this limitation is overcome when integrated with GIS (Fistikogli & Harmancioglu, 2002).
- Deposition is not included in the USLE. Nor does it model wind-, mass-, tillage-, channel- or gully erosion, it is developed to simulate inter-rill and rill erosion (sheet and rill erosion) (Fistikogli & Harmancioglu 2002, FAO 1996, Stone & Hilborn 2000).
- Also the interaction between factors is not taken in consideration. For example the influence of the equation factors from a slope with a specific vegetation cover and a characteristic soil type are applied separately and do not interact (FAO 1996). This means that a potential synergy or side effect of combined conditions may be lost.
- Finally the equation is only valid for long term conditions, why it is not valid to simulate the effects of individual storms (FAO 1996).

2.4. GIS and the USLE/GIS approach

As mentioned in chapter 2.3, the non-existing spatial distribution of the USLE is overcome by integration with GIS. In fact the USLE is a very powerful tool when integrated with GIS, especially for the conditions in developing countries where lack of data rule out reliable applications of more advanced, physically based models (Beskow et al, 2009). The simplicity of the USLE is most likely the main reason why it is still widely used where data is insufficient.

2.4.1. *Concept of the model*

A GIS is not restricted to display and edit digital maps, other data can be stored and related to a position or object as well. Thematic layers can represent data elements in the GIS – for example maps of topography, geology, soils and precipitation as well as information on population and archaeology etc. (*Figure 6*) (Larsson & Harrie, 2005).

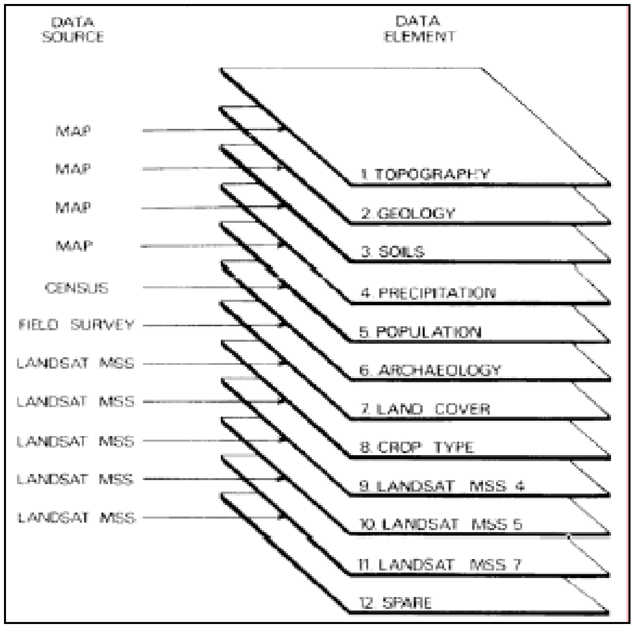


Figure 6; *Principle of the thematic layers in a GIS (Larsson & Harrie, 2005)*

In order to apply the USLE in a GIS, every parameter is organized as a thematic layer which is providing a spatial distribution. The layers need to be of the type 'raster', which means that they are in the form of grid nets (matrixes). In the spatial distribution of the raster, every grid cell has a unique parameter value and the model is executed by an overlay operation that multiplies all the parameter layers mathematically. This means that every single cell is overlaid (multiplied) with its spatially corresponding cells in the other parameter layers, completing the multiplication of the equation. The output of the model is a combined layer where every single cell value is the product of the equation. Finally the whole layer is summed and the average annual soil loss per hectare is calculated by taking the total catchment area in consideration. An example of the overlay operation is displayed in *Figure 7*, where 'C' is the output raster when 'A' and 'B' is overlaid by multiplication.

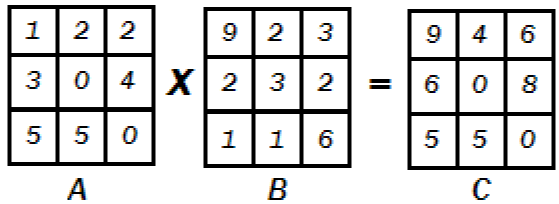


Figure 7; ***Raster multiplication overlay operation. Every cell in layer A is multiplied by its corresponding cell in layer B. C is the resulting layer.***

2.4.2. Comparison of methods – recent studies

By studying different articles on erosion prediction by USLE/GIS methodology it is made clear that there are some different approaches of using this concept. Determination of the USLE-factors can be performed in different ways depending on available data and other conditions such as catchment size. *Figure 8* shows the working steps of Fistikogli & Harmancioglu (2002) when determining soil loss with USLE integrated in GIS.

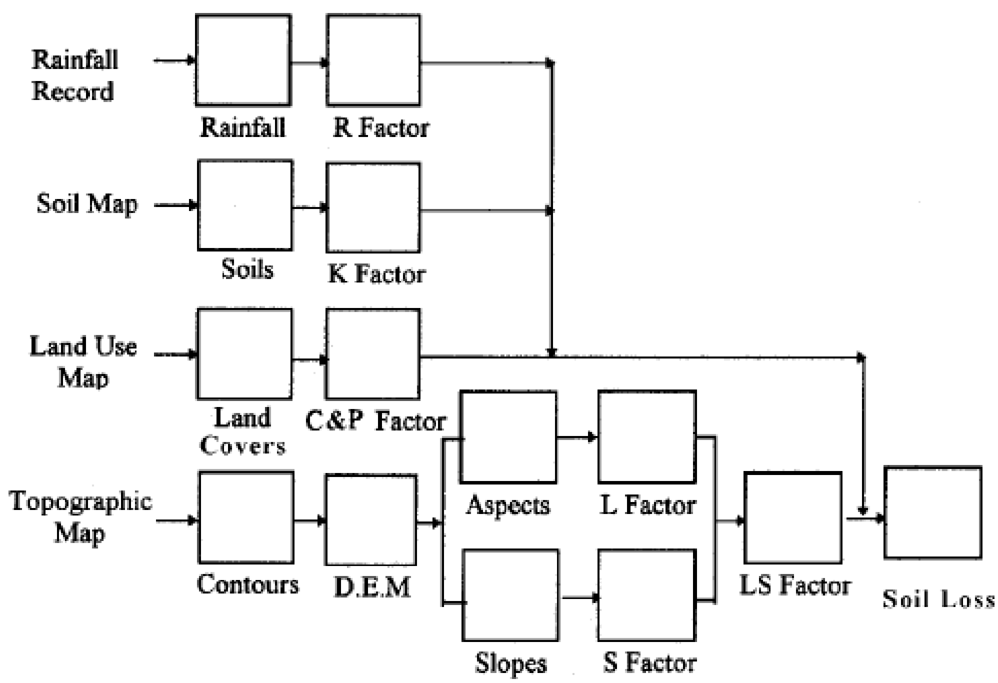


Figure 8; Working steps for determination of USLE-factors and finally soil loss estimation. (Fistikogli & Harmancioglu 2002)

To display how this approach can be performed, the methodology used in three recent studies are hereby compared; firstly there is a study on the Himalayan '*Chaukhutia'* watershed, 572 km^2 (Jain et al., 2010). Secondly there is a report from Brazil on a larger basin, *'Grande River Basin',* 6273 km^2 (Beskow et al., 2009) and last the Tunisian study of the smallest '*Jannet'* catchment, 5.41 km^2 (Jebari, 2009).

The ***K-factor*** was derived and digitized from soil maps, national geological surveys and classifications in literature in all three studies (Jebari, 2009; Beskow et al., 2009; Jain et al, 2010). Beskow et al (2009) mentions that actual field measurements would be to expensive and time consuming while Jebari (2009) has used complementary field work in addition to available data.

For the ***LS-factor***, Jebari (2009) has used a *DEM (Digital Elevation Model)* derived from a topographical map with a vertical resolution of 10 meters, scaled at 1:50000. A constant slope length *L,* set to 15 meters, was used over the whole catchment and then the LS- factor was calculated for slopes classified in three classes using the equation (*eq. 2*) recommended by Morgan and Davidson (1991) (Jebari, 2009). Jain et al (2010) used a 50 m grid cell resolution for the DEM, derived from a map scaled at 1:50 000 interpolated in the GIS-software. The LS-factor was determined with the equation from the theoretical relations of the *unit stream power theory* (*eq. 3*) (Moore et al, 1986a, 1986b, 1992) “as this relation is best suited for integration with GIS” (Jain et al, 2010). Beskow et al (2009) used a similar (*eq. 3*) relation as Jain et al for *LS,* with some minor changes in the approach, using different categories for different slopes and changing equation constants regarding to slope steepness. *L* and *S* were determined separately using a 30 m grid size resolution for the DEM. The L-factor was derived from a fixed field slope length equal to the grid cell size (30 m) for three categories of slope; 0-3%, 3-5%, +5%. The S-factor was determined separately for two categories; 0-9% and +9%. In the study of Beskow et al (2009) the slopes were generally steep with a 17.21% average.

Concerning the ***R-factor***, both Jebari (2009) and Jain et al (2010) used a constant R-factor value for the entire catchment. Beskow et al (2009) used six rainfall gauges evenly spread over the catchment. The GIS-tool was used to determine the representation of each station in terms of catchment area, resulting in a thematic layer for the R-factor.

Determination of the ***P-*** and ***C-factor*** for the Jannet catchment was performed through interpretation of aerial photos at scale 1:20000, having both factors divided into six classes (Jebari, 2009). In the Chaukhutia watershed, satellite images geo-coded at 30m pixel cell resolution where used for determination of the C-factor, divided into six classes (Jain et al, 2010). The P-factor was assumed to be homogenous and estimated to 0.7 for the entire catchment (Jain et al, 2010). Beskow et al (2009) considered the entire Grande River Basin unaffected by conservation practices, why the P-factor was set to 1.0. The C-factor map for the Grande River Basin was developed based on previous Brazilian studies, derived from satellite images into six classes (Beskow et al, 2009).

3. Materials and Method

3.1. Site presentation

The two catchments studied are 'Sadine2' and 'Mrichet', located in north-central Tunisia in the Dorsal - Mountains (the easternmost parts of the Atlas chain) (*Figure 9*). The highest peak of the Dorsal is at 1,544 m above sea level and the mountains cover an area of 12,490 km^2. The Dorsal is located within the 400 mm/year precipitation isohyet, which is considered the limit for agriculture (Jebari, 2009). The two studied catchments are included and monitored in the EU-funded HYDROMED-project, covering a total of approximately 30 small experimental reservoirs in the Dorsal, for which precipitation is recorded (Jebari, 2009).

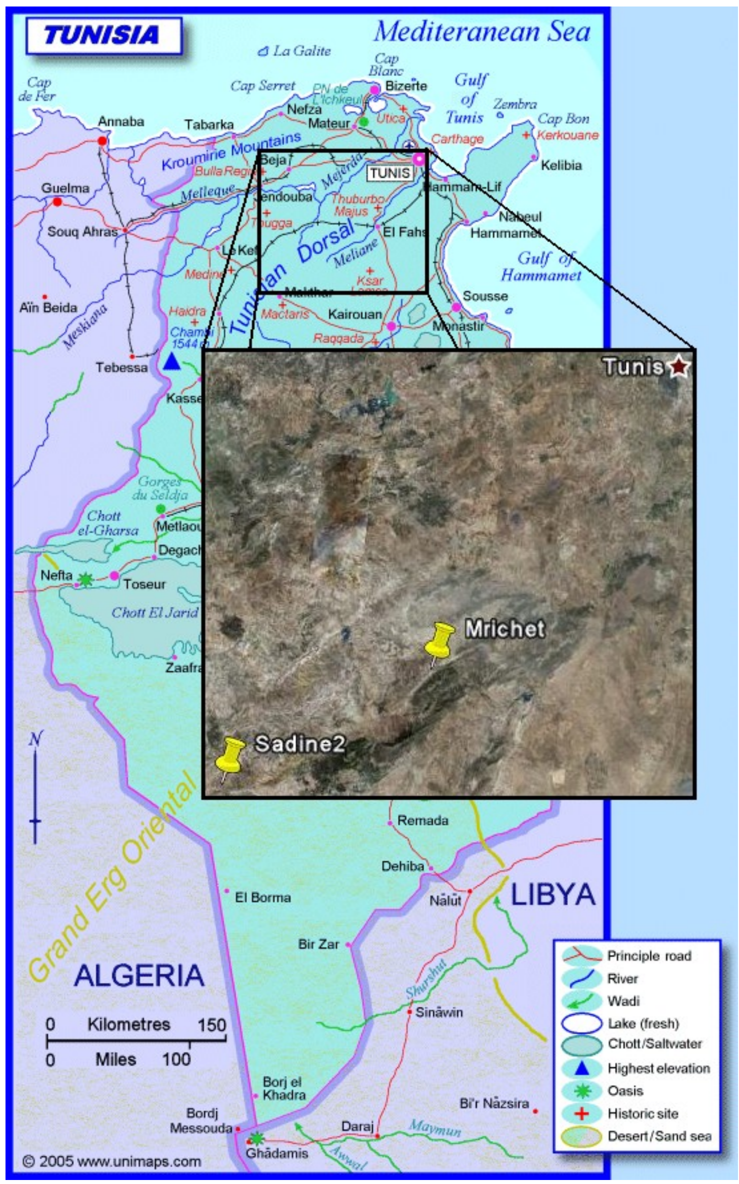


Figure 9; *Location of the studied catchments, 'Mrichet' and 'Sadine2' (Jebari, 2009)*

3.1.1. Mrichet

Mrichet catchment (*Figure 10*) has an area of 1.58 km^2 (158ha) of which 92% is agricultural land (Convention CES/IRD, 1996-2002). Elevation ranges within 140 meters and the average slope is 11.1% (Jebari et al, 2010). The reservoir of Mrichet was constructed in 1991 and holds a total volume of 42 400 m^3 of which 22.7 % (9 610 m^3) was silted at the last measurement, 1999-09-24 (Convention CES/IRD, 1996-2002). No date is given for installation of a detailed automatic precipitation recording device, however records are available from 1993-09-24 to 2002-09-25. The average long-term precipitation (1969-1998) is about 407 mm/yr with a standard deviation of 121 mm/yr (*Figure 11*). The observed average annual soil loss A_{ave} is 11.4 ton ha^{-1} yr^{-1} (recorded from 1991 to 1999) and the observed maximum annual soil loss A_{max} is 19.5 ton ha^{-1} yr^{-1} (recorded 1996-05-29 to 1998-03-17).

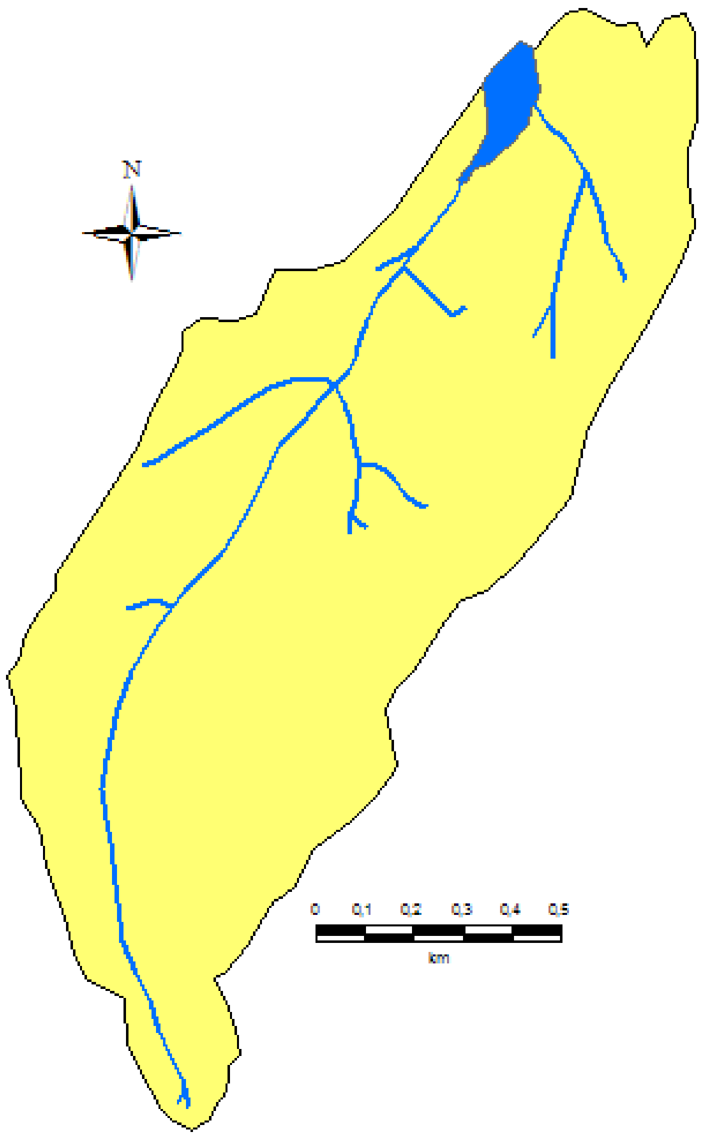


Figure 10; ***The hydrological network of 'Mrichet'***

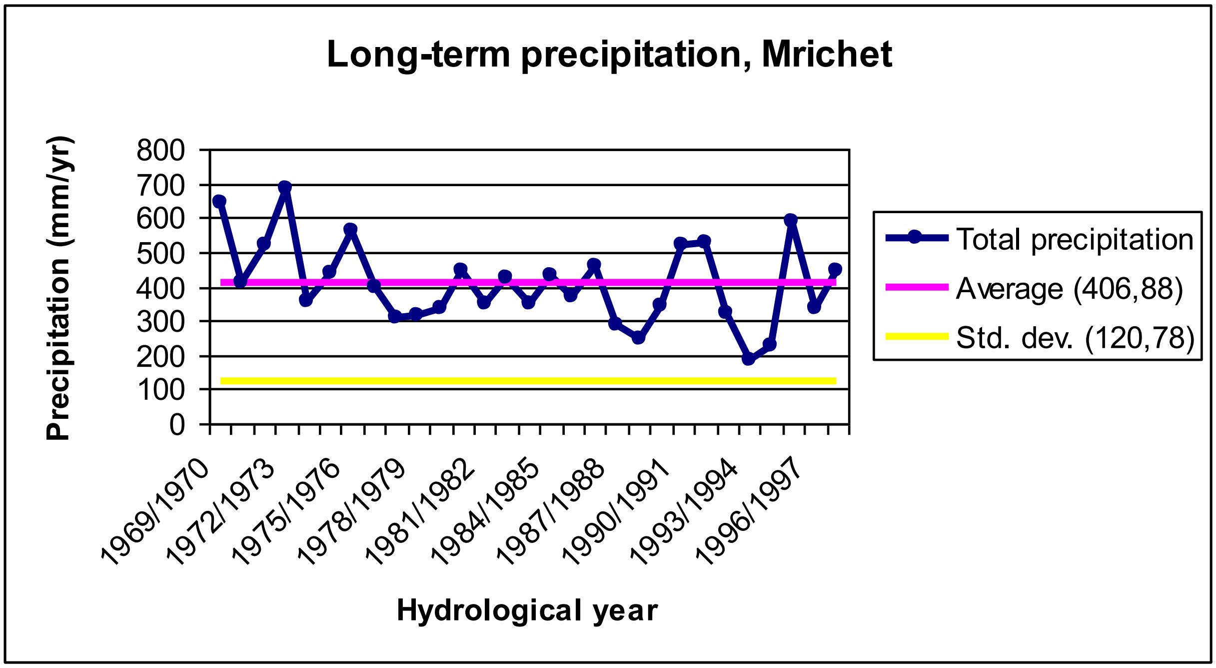


Figure 11; ***Long-term precipitation records of 'Mrichet'***

3.1.2. Sadine2

Sadine2 catchment (*Figure 12*) has an area of 6.53 km^2 (653ha) of which 62% is agricultural land (Convention CES/IRD, 1996-2002). Elevation ranges over 436 meters and the average slope is 17.0% (Jebari et al, 2010). The reservoir of Sadine2 was constructed in 1990 and holds a total volume of 108 800 m^3 of which 98.0 % (106 585 m^3) was silted at the last measurement, 2000-07-12 (Convention CES/IRD, 1996-2002). A detailed automatic precipitation recording device was installed 1994-02-28 and records are available to 1998-09-16. The average precipitation (1969-1998) is about 512 mm/yr with a standard deviation of 132 mm/yr (*Figure 13*). Observed average annual soil loss A_{ave} is 24.5 ton ha^{-1} yr^{-1} (recorded 1991-1999) and the maximum annual soil loss A_{max}= 59.1 ton ha^{-1} yr^{-1} (recorded 1996-05-29 till 1998-03-17).

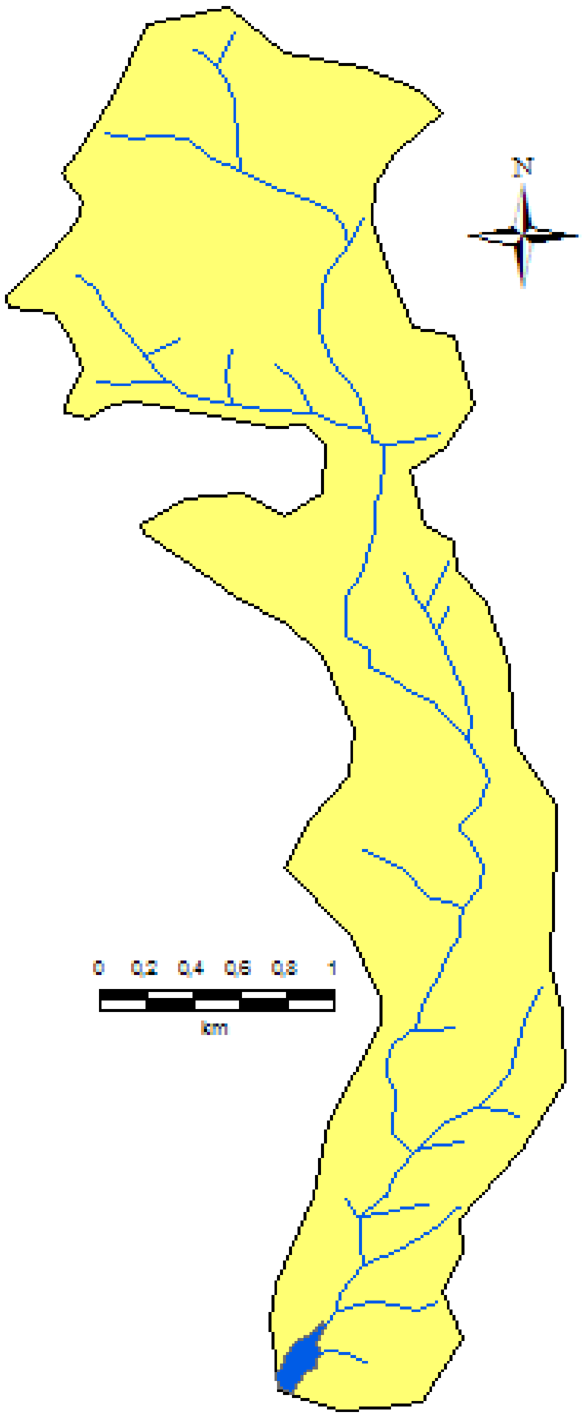


Figure 12; ***The hydrological network of 'Sadine2'***

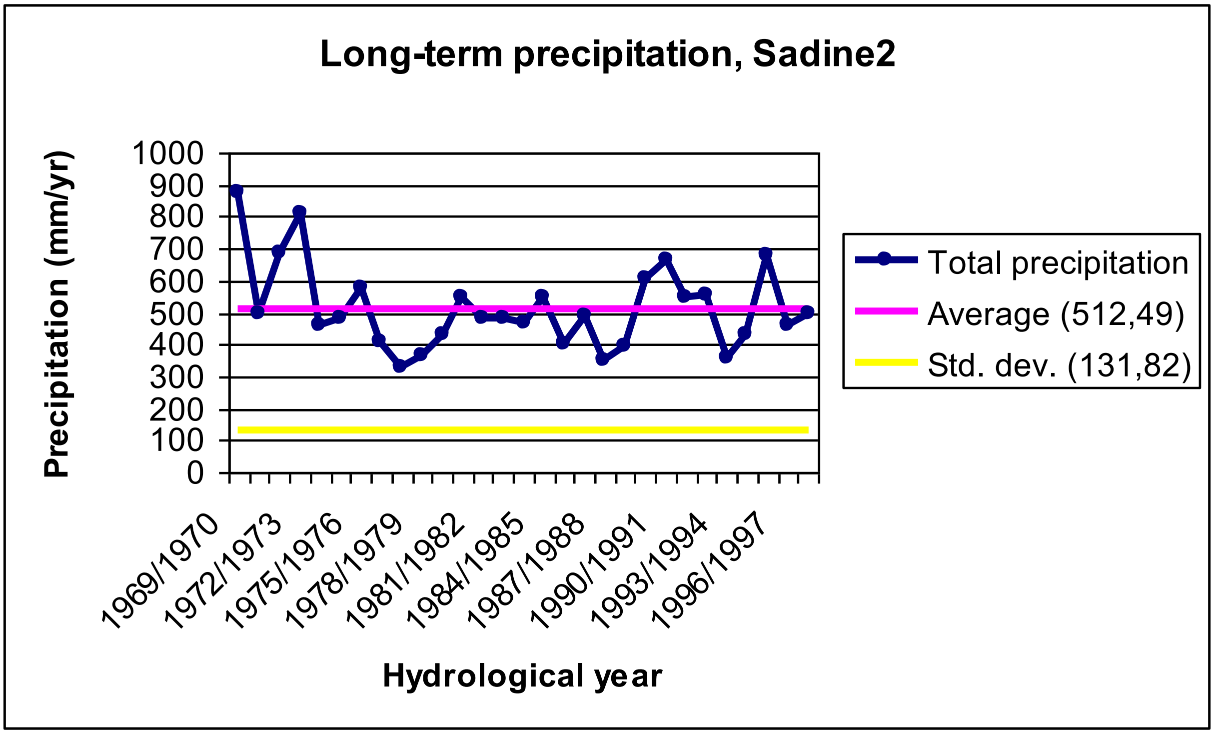


Figure 13; ***Long-term precipitation records of 'Sadine2'***

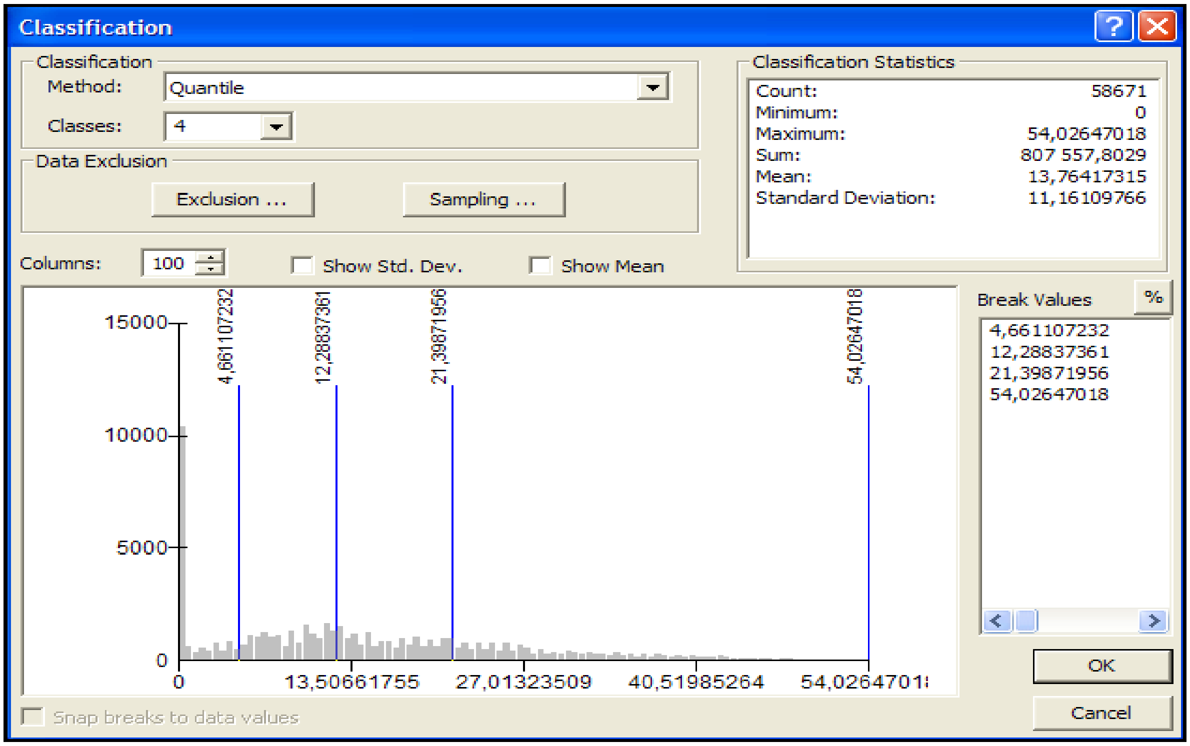
3.2. Method

3.2.1. Arranging model layers and determination of USLE-factor values

Work procedure of arranging the layers was performed in GIS-software *ArcView GIS 3.3* and *ArcMap 9.2*. Software *RSI ENVI 4.2* was used for geo-referencing of pedological maps, land use maps and satellite images. Final combination of the raster layers was made in *ArcView GIS 3.3* with the function *'combine'* in the *GRID Tools* extension. Screen prints of generated layers and factor values are found in *Appendix B*. Geo-referenced satellite images are found in *Appendix C.*

3.2.1.1. Topography (LS)

Work procedures for generation of the LS-layers were identical for both Mrichet and Sadine2. Elevation curves where digitalized into a line layer from a topographic map with a 10 m vertical resolution and 1:50000 scale. Catchment borders were defined as a polygon layer and surrounding elevation points were digitalized into a point layer. From these layers (lines, polygon and points) a *DEM* tin-file (Digital Elevation Model in *.tin-file format) was generated. The DEM was transformed into a raster layer of elevation from which a raster layer of slope was derived. The slopes were then classified into 4 classes, equally separated according to their cell number representation in the distribution (*Figure 14*).



Figur 14; *Example (Sadine2) of slope classification. All slopes were equally divided into four classes due to representation in cell numbers. Number of cells are on the Y-axis, slope in % is on the X-axis.*

Finally the LS-factor values for every class were calculated through the equation (*eq.2*) recommended by Morgan and Davidson (1991). The slope steepness S used was the average value of every class. The slope length L was difficult to estimate properly and therefore assigned the value of 22 m, the same length as the original Whichmeier experimental plots (FAO, 1996).

3.2.1.2. Soil Erodibility (K)

For Mrichet, the K-factor layer was digitalized and divided into polygons from a pedological map (Convention CES/IRD, 1998). The K-factor layer for Sadine2 was generated from a digital soil map (a GIS polygon shape file) received from the *'Tunisian Ministerè de L'agriculture et des Resources Hydrologiques'* (2010). The K-factor values (*Table 2*) for both catchments were deduced from literature (Zante et al, 2001; Dangler et al, 1976; Prog. D'actions Prioritaires, 1998) and consulting local experts.

Table 2; ***Theoretically determined K-factor values for the soil types represented in both catchments.***

Soil type	K-factor value
Vertisol	0.019
Brown, calcareous / vertic	0.020
Lithosol / regosol	0.021
Brown, calcareous	0.033
Raw mineral	0.036
Less developed / vertic	0.036
Lithosol / rendzina	0.050
Lithosol / brown calcareous	0.050
Complex	0.050
Less developed	0.054
Rendzina	0.100
Water body	0.000

3.2.1.3. Rainfall Erosivity (R)

In both sites the rainfall erosivity factor was considered constant over the entire catchment area. This is a generalization due to lack of data, having only one rain gauge on each site. The R-factor value was determined according to the Whichmeier method (OMM/WCP, 1983) (see *Appendix A* for calculations); only taking storm events exceeding 12.7 mm into consideration and using the 30-min maximum intensities I_{30}. In comparison a second value was also calculated for 15-min intensities I_{15}, as proposed by Jebari (2009) for R-factor values in semiarid regions. The rainfall data used was given in 5-min intervals of the event intensity. R-factor values were determined for two periods. The first was for the total time period of available rainfall data using the *complete* hydrological years (1st September to the 31st August); *'HY-period'.* The second was for the period of maximum observed erosion; 'A_{max}*-period'* (see '*Appendix A'* for more details concerning R-factor determination).

Mrichet R-factor - data conditions and determination;

- Data was available from 1993-09-24 to 2002-09-25 and no data was missing within the period of measurements. The period covers eight complete hydrological years from 1994/1995 to 2001/2002. The maximum observed A_{max} was observed from 1996-05-29 to 1998-03-17.
- The period had a total of 55 valid events of which 54 were within the eight hydrological years, giving an average of 6.75 events / year for the HY-period.
- HY-period; $\mathbf{R_{15} = 159,49}$ and $\mathbf{R_{30} = 111,34}$ *(ton* $ha^{-1}\,yr^{-1}$*)*
- A_{max}-period; $\mathbf{R_{15} = 168.01}$ and $\mathbf{R_{30} = 119.03}$ *(ton* $ha^{-1}\,yr^{-1}$*)*

Sadine2 R-factor - data conditions and determination;

- Data was available from 1994-03-24 to 1998-09-16 and no data was missing in the period of measurements. The period covers four complete hydrological years from 1994/1995 to 1997/1998. The maximum observed A_{max} was observed from 1994-06-14 to 1996-05-07.

- This period had 30 valid events of which all are within the four hydrological years, giving an average of 7.5 events / year for the HY-period.

- HY-period; $\mathbf{R_{15} = 115.82}$ and $\mathbf{R_{30} = 85.47}$ *(ton ha^{-1} yr^{-1})*

- A_{max}-period; $\mathbf{R_{15} = 71.17}$ and $\mathbf{R_{30} = 62.84}$ *(ton ha^{-1} yr^{-1})*

Figure 15 shows the determined R-factor values for the different time periods.

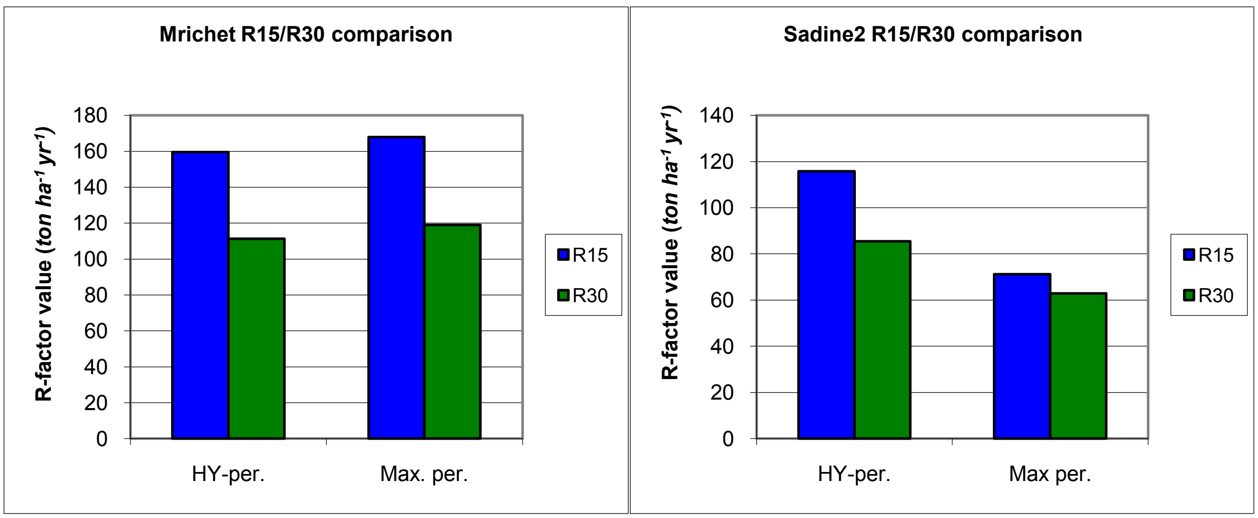


Figure 15; ***R-factor values of 'Mrichet' and 'Sadine2'. In Mrichet, the R-factor is slightly higher for the A_{max}-period, for Sadine2 it is lower.***

3.2.1.4. Crop management factor (C)

For both catchments the C-factor layer was constructed from a land use map (Convention CES/IRD, 1998) digitally divided into polygons representing each land use class. Parts of this layer were then revised or confirmed by in-field observations and by studying *Google Earth* satellite images. C-factor values were determined from the report of Zante et al (2001). Missing values were taken from previous studies (Jebari, 2009; Beskow et al, 2009; Jain et al, 2010; Erdogan et al, 2006) or assumed by estimation. *Table 3* displays the different land use classes used for Mrichet and Sadine2 with corresponding C-factor values.

Table 3; ***The determined C-factor values for the catchments***

Land use	C-factor value
Water body	0.000
Forest, dense	0.015
Forest, light	0.100
Habitats	0.100
Roads	0.130
Tree plot, cherry	0.180
Scrubland	0.250
Crop-fallow rotation	0.500
Wedi	0.700

3.2.1.5. Conservation practice factor (P)

The P-factor layer was drawn as a polygon layer from geo-referenced satellite images (Google Earth, 2010), and then converted to raster layers.

The only observed conservation practices for Mrichet were some banquettes in the north east of the catchment (*Figure 16*).

Figure 16; ***Banquettes in Mrichet***

These banquettes are most likely to have a very low influence due to the small area they affect, but are still taken into consideration for the P-factor. The area connected up-slope of each banquette was assigned the value of 0.10. According to Zante et al (2001) this is the conservation practice value for ‘banquettes with or without plantations’ on 5-10% slopes.

In Sadine2 there are some conservation measures done in the cropped lands just upstream the reservoir. Here the banquettes are more considered as ‘strings of rock’ (*Figure 17*). When separated by an approximate distance of 25 meters the P-factor will be assigned the value 0.45 (Zante et al, 2001) for the area.

Figure 17; *Strings of rock in Sadine2*

3.2.2. Field Work

Field work was performed with the guidance and assistance of the *Department of Soil and Water Conservation Practices* in Siliana, close to the study areas. The field work aimed to experimentally determine K-factor values to compare with the theoretically determined ones. Also observations were made in the landscape to verify topography and land use. Complete soil samples were taken for the Mrichet catchment.

3.2.2.1. Soil sampling

Soil samples were taken in order to analyze soil texture, structure and organic content (*Figure 18*). Five different sub-samples were taken in the surface layer (approximately 10 cm) for every soil class in the pedological map. These where then mixed and combined into a final sample for every soil class, sent to analysis in the lab.

Figure 18; *Field soil sampling with local experts*

3.2.2.2. Permeability - Infiltration Tests

The infiltration capacity of each soil class in both catchments was measured with a field test. Two pipes were arranged on horizontal and non-cropped soil (*Figure 19*). The purpose of the outer pipe is to maintain a constant downward infiltration flow surrounding the inner pipe. This will reduce the lateral infiltration and direct the infiltrating water of the inner pipe downwards (*Figure 19*). A constant head of 30 mm is kept in the inner pipe while infiltrated amount of water (required refill to maintain the 30 mm head) is noted in a specific time interval ranging over 60 minutes.

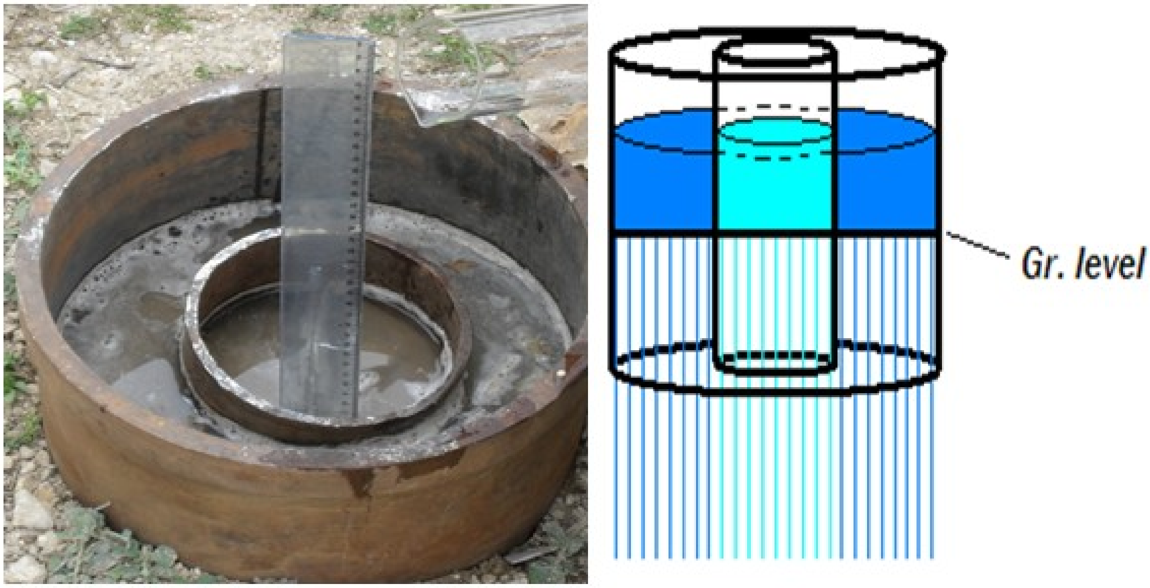


Figure 19; *Infiltration tests in the field - the infiltrated water is measured over 60 minutes while keeping a constant head. Lateral infiltration is reduced by using an additional outer ring with a constant head.*

3.2.2.3. Soil aggregate structure tests

The durability in the aggregates of the soil types was also observed by placing a lumped sample in water and study how it was affected. In most samples it was seen in a few minutes how the cohesive and gravitational forces acted on the aggregate when soaked (*Figure 20*).

Figure 20; Soil aggregate test to study the durability of a soaked sample.

3.2.2.4. Field observations

The field visits also aim to confirm the reality of the catchments with how they are interpreted from available data. Comparisons were done with reality and the generated topography (LS), land use (C) and conservation practices (P) maps to confirm the conditions of the model as well as making corrections. In Mrichet for example, an apple tree orchard in the map was missing, while a cherry tree plot not marked on the map was found. Also in Sadine2 there were differences in observed reality and land use maps; the land use map class 'forest' had a very low density of vegetation and was revised to 'light forest' due to the field observations. Also two different definitions of the catchment border were found for Sadine2, one by Convention CES/IRD (1998) and on by Convention CES/IRD (1996-2002). The definition to use could be determined through field observations and further comparisons with the topographical map.

3.2.3. Calibration

After defining all input data the model was calibrated against observed soil loss values. The methodology of the calibration was to compare estimated and observed soil loss and adjust the input parameters to match the model with observed reality. The general methodology was to calibrate on the Mrichet catchment since it had a less complex topography, and then confirm the settings by running the same conditions for Sadine2.

3.2.3.1. K-, C-, and P-factor layers

The content of the K-, C- and P-factor layers were not really considered for calibration since it is more or less defined by the available input data and cannot be changed without changing the definition of these. USLE-factors considered in the calibration were thereby the R-factor and the LS-factor.

3.2.3.2. R-factor

As mentioned, the R-factor is considered constant for the entire catchment and is represented by a single value. As seen in *Figure 21* it does not seem to be any correlation between the calculated R-factor values for the two periods considered and the different observed soil losses for the same periods; in Mrichet the R is only slightly increased and for Sadine2 it is actually decreased for the 'A_{max}-period'. Based on the recommendations in the Whichmeier approach to use long term data, preferably 20 years (FAO, 1996), and the non-existing correlation to the 'A_{max}-period', the R-factors were determined from the 'HY-period' was used for the calibration. It was also found that the soil loss was more accurately estimated with R_{15} as proposed by Jebari (2009), why this value was used.

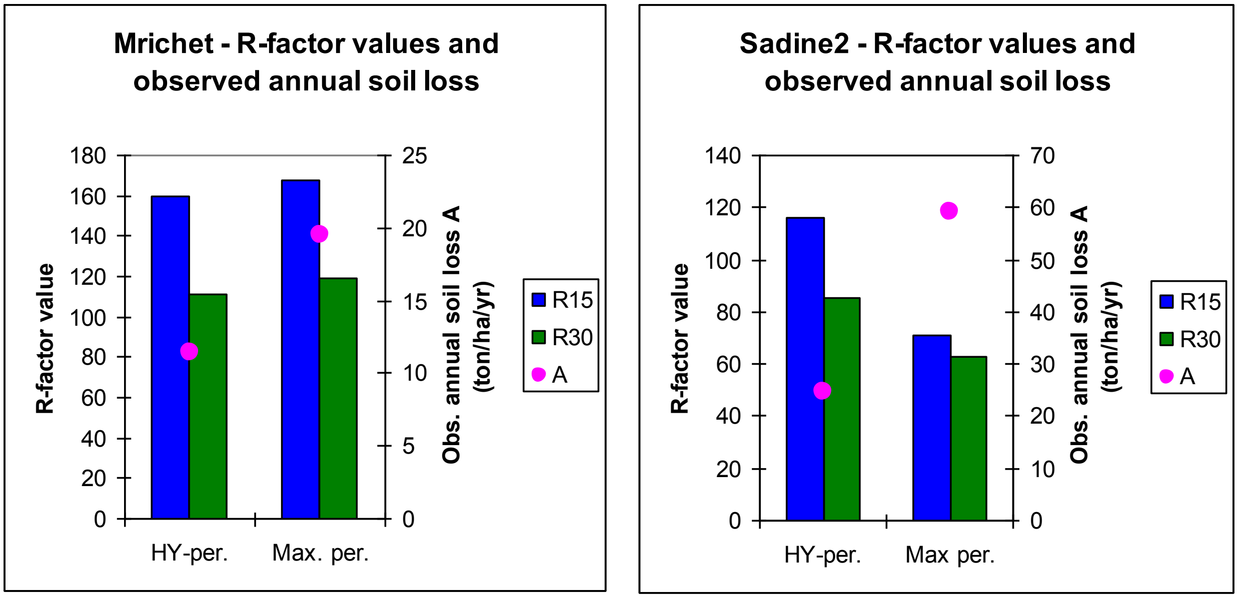


Figure 21; Comparison of soil loss (A) and R-factor values (R15 and R30) for the HY-period and the A_{max}-period.

3.2.3.3. LS-factor layer

Topographic factor LS is represented by a more complex layer. The slope steepness is very much affected by how you chose the grid cell dimensions in the DEM. Wu et al (2005) states that the estimation of soil loss by empirical models decreases significantly when the grid cell size is increased. This is mainly due to the reduction in general slope steepness. The next step in the calibration was therefore mainly focused on determining the right conditions for the LS-factor layer in terms of the grid cell resolution. In order to calibrate the model it was executed using a 10, 15, 20, 25, 30, 40 and 50 meter grid cell size.

3.2.3.4. The Grid Cell Dimension

Also when combining raster layers in an overlay operation it is necessary to use uniform cell dimensions and distribution for all layers (Larsson & Harrie, 2005). In case of differences in cell dimensions it is possible that the software will distort the values due to a generalization in the operation algorithm (Larsson, 2010). In order to overcome this issue, all layers are generated with the same grid cell resolution as the LS-factor layer throughout the calibration.

3.2.3.5. Calibration Summary

- K-, C- and P-factor layers are not considered for calibration
- The R-factor value best suited is R_{15}
- The LS-factor layers were generated for 10, 15, 20, 25, 30, 40 and 50 meter grid cell sizes.
- All layers were generated in the same grid cell sizes as the LS-factor layer.

4. Results

4.1. Soil Loss Estimation

The spatial distribution maps of erosion in Mrichet and Sadine2 catchments are shown in *Figure 22* and *23.* The result is displayed in 30x30 meter grid cells, which is the median size from the calibration. The erosion is classified in two different classifications. According to Whichmeier and Smith (1978) the maximum tolerable soil loss (12 ton ha^{-1} yr^{-1}) is defined as “the maximum level of soil erosion that will permit a level of crop productivity to be sustained economically and indefinitely”. Also Masson (1971) used a classification for Tunisian semiarid soils where maximum tolerable soil loss is graded to 2.5, 5 and 10 ton ha^{-1} yr^{-1} for a thin, average and thicker soil respectively.

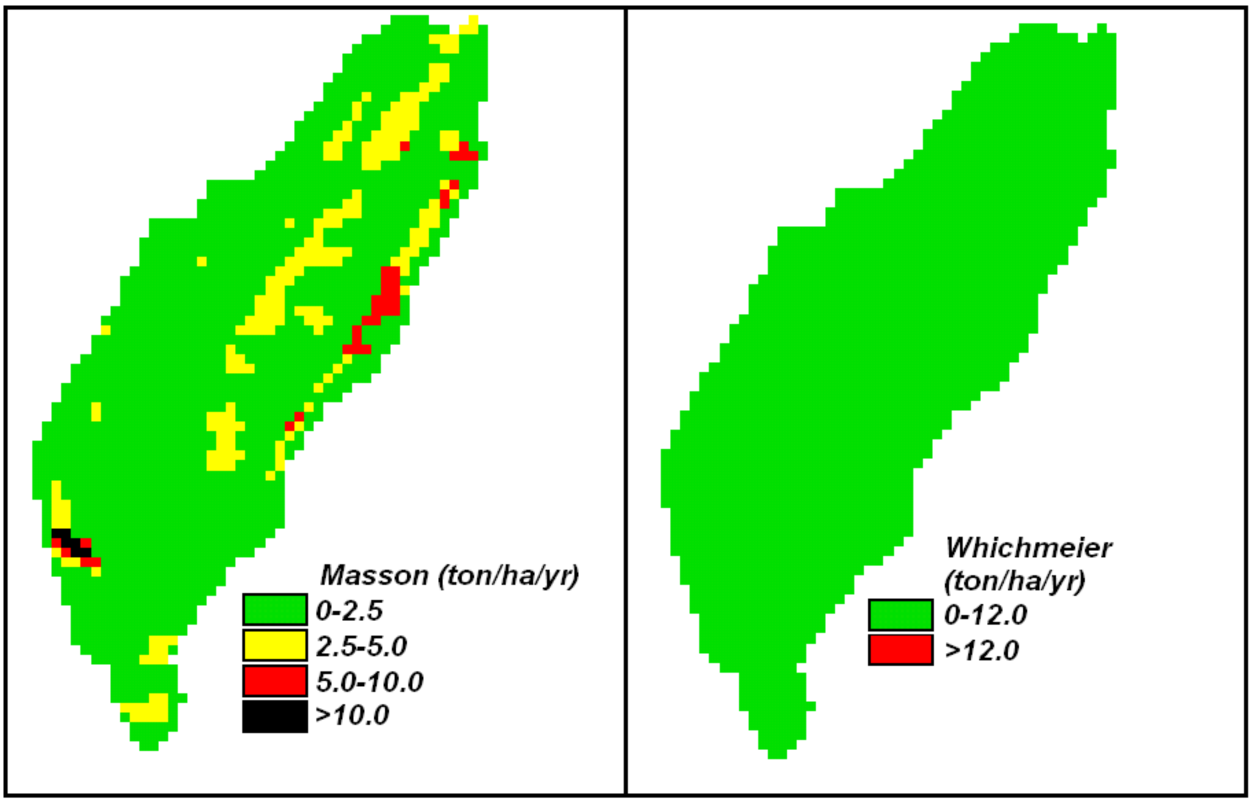


Figure 22; ***Spatial distribution map over modeled erosion in Mrichet catchment. The erosion is displayed in both Masson’s and Whichmeier’s classification.***

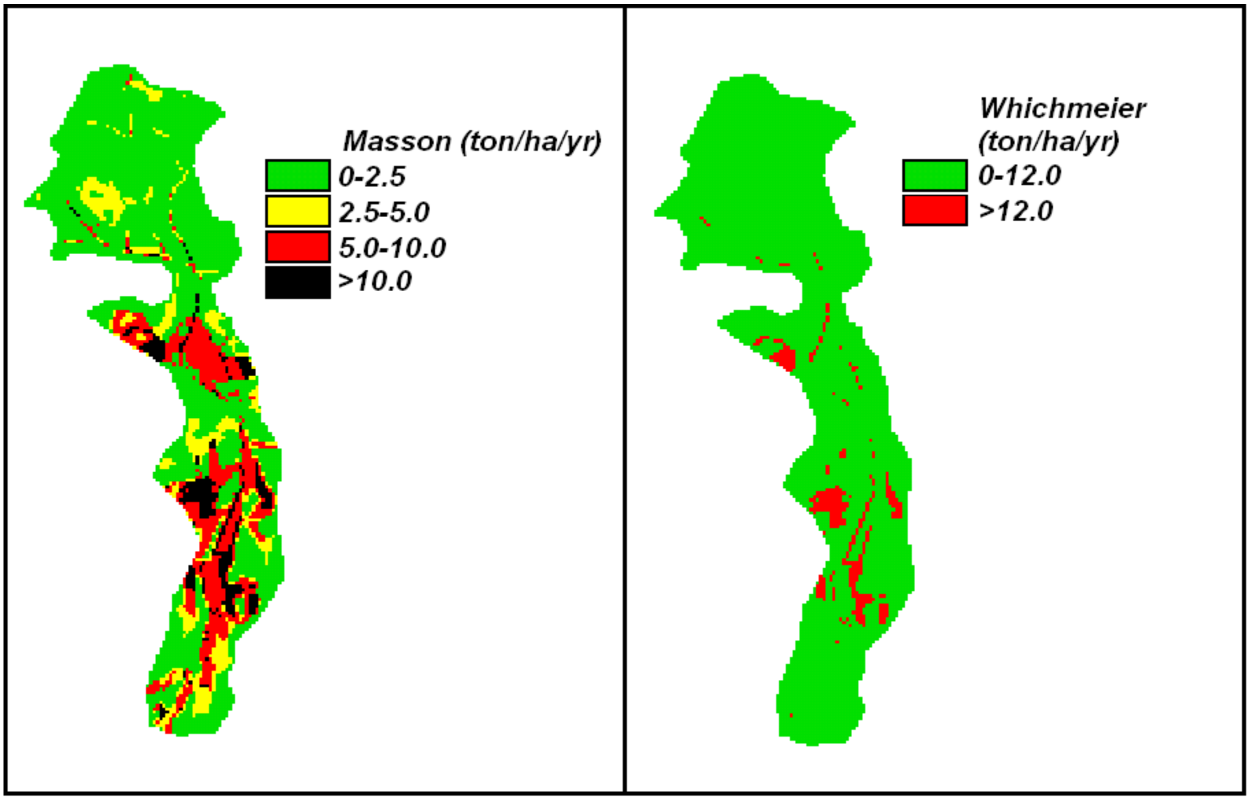


Figure 23; ***Spatial distribution map over modeled erosion in Sadine2 catchment. The erosion is displayed in both Masson's and Whichmeier's classification.***

Figure 24 (Mrichet) and *25* (Sadine2) shows the simulation results in terms of catchment average annual soil loss, plotted against the different grid cell sizes used in the calibration. The comparative observed erosion is for Mrichet ***11.4*** *ton* ha^{-1} yr^{-1} and for Sadine2 ***24.5*** *ton* ha^{-1} yr^{-1}*.* The modeled soil loss is very much too low in comparison with observed siltation records. However, if comparing the deviation from the observed data it is seen that the errors are in the same order of magnitude in both catchments (*Figure 26*).

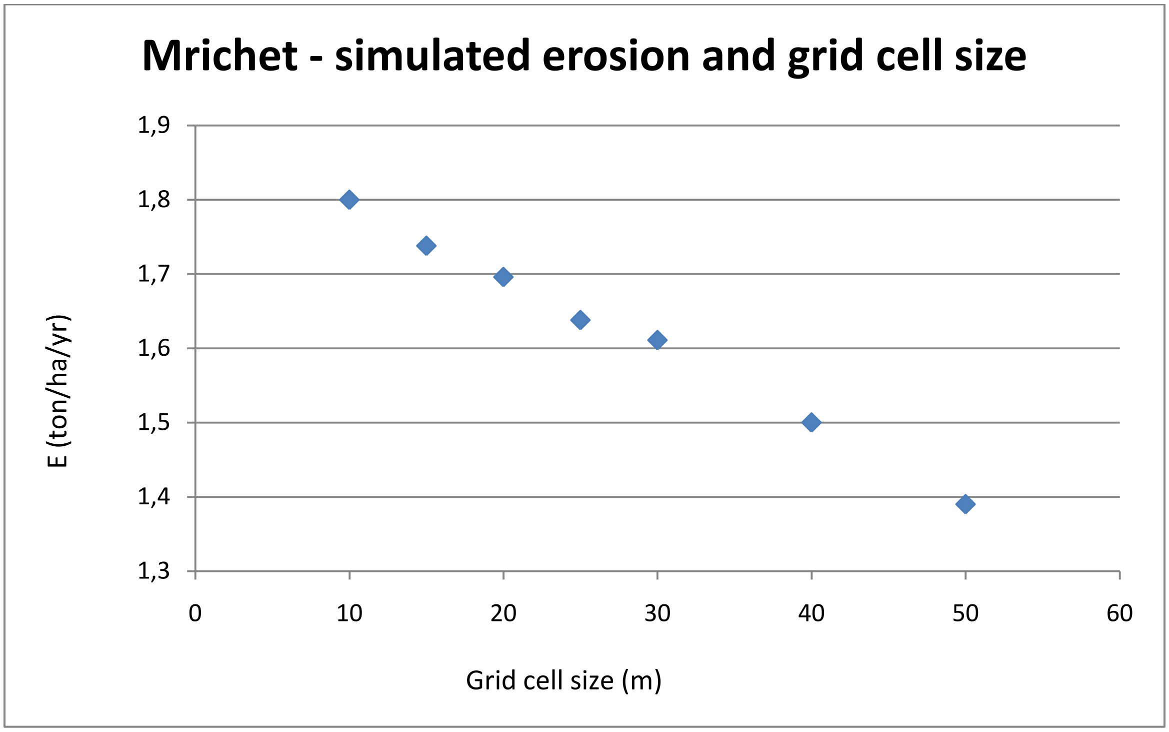


Figure 24; ***Calibration results for Mrichet catchment, the comparative observed erosion is 11.4 ton ha^{-1} yr^{-1}.***

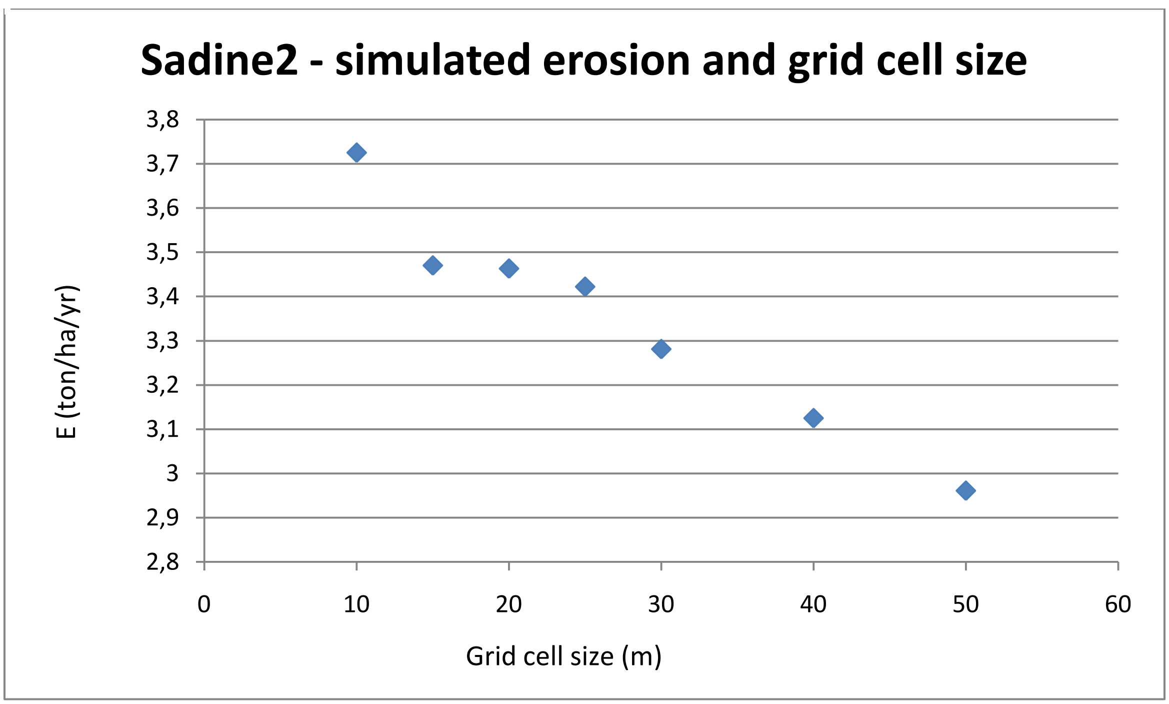


Figure 25; ***Calibration results for Sadine2 catchment, the comparative observed erosion is 24.5 ton ha^{-1} yr^{-1}***

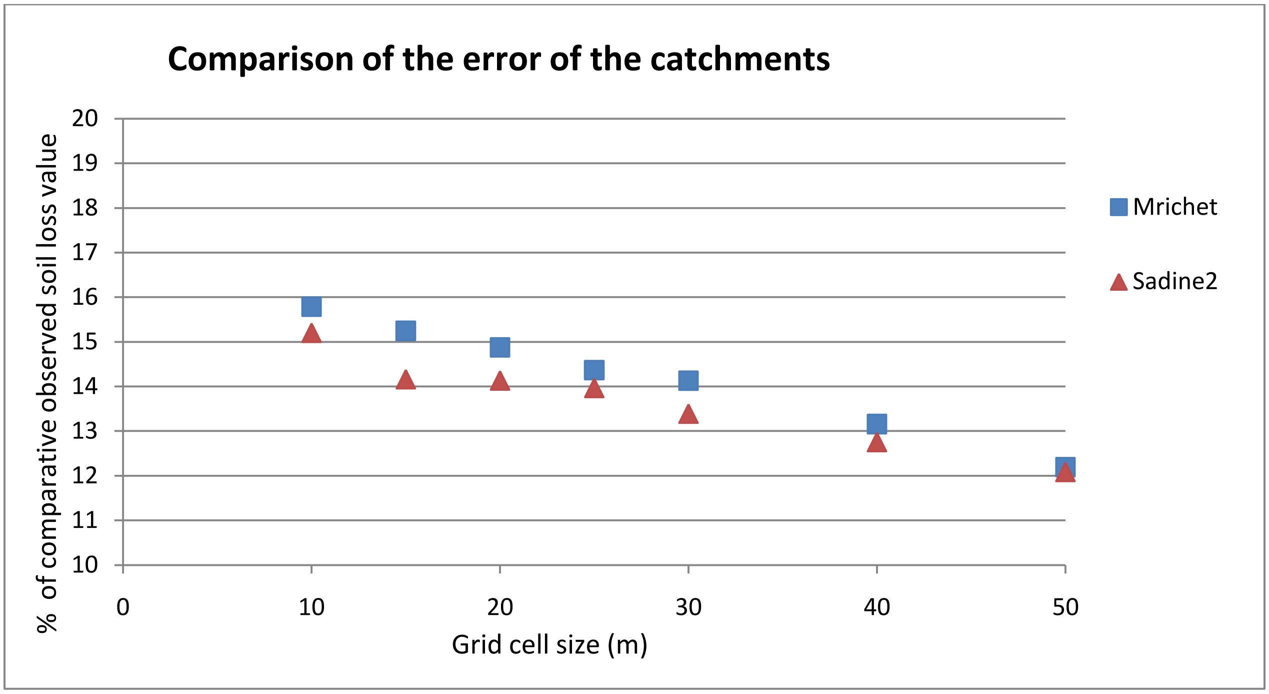


Figure 26; ***The errors of both catchments are in the same order of magnitude***

4.2. Field Work

The determination of comparative K-factor values was performed according to the USLE-principle in chapter '*2.3.1.2. Soil Erodibility Factor (K)'. Table 4* shows the lab analysis data used to determine experimental K-factor values. *Figure 27* shows the comparison with the theoretical values used in the model.

Table 4; ***Determination of experimental K-factor values were 'Fine sand + silt' is grain sizes 0.002-0.100 mm, 'Sand' is 0.100 – 2 mm, 'O.M.C.' is organic matter content, 'S.C.' is structure class, 'P.C.' is permeability class, 'K.us' is K-factor value in US-units and K.si is K-factor value in SI-units.***

Soil	Fine sand + silt (%)	Sand (%)	O.M.C. (%)	S.C. (1-4)	P.C. (1-6)	K.us	Ksi
1. Less dev. / vertic	69,75	10,25	1,0	2	2	0,42	***0,055***
2. Lithosol / regosol	59,5	10,25	1,0	2	1	0,29	***0,038***
3. Rendzina	56,5	18,5	1,5	1	n/a	n/a	***n/a***
4. Lithosol / rendz.	66,75	8,25	1,0	2	1	0,35	***0,046***
5. Lithosol / brown calc.	56,75	13,25	0,9	2	1	0,26	***0,034***
6. Brown, calc. / vertic	49,5	13,5	1,3	3	2	0,24	***0,032***
7. Brown, calcareous	47	17,75	1,3	3	3	0,27	***0,036***

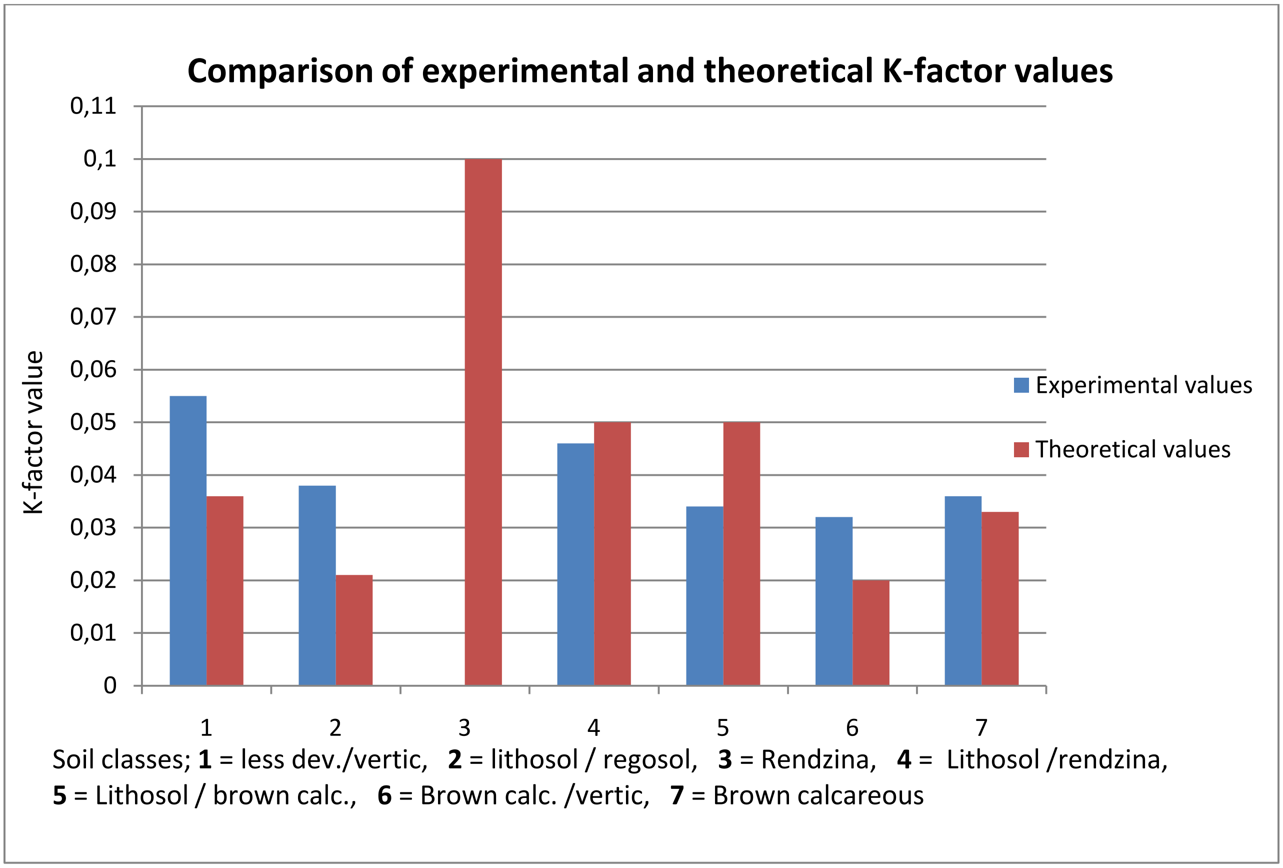


Figure 27; ***Comparison of experimental and theoretical K-factor values in Mrichet catchment.***

5. Discussion

5.1. Sources of Error –Generalizations, Approximations and Model Limitations

All working steps in creating the thematic layers of the model contain approximations and generalizations of data to some extent. When topographic maps and satellite images are digitalized it is hard to achieve exact precision due to low resolutions, low scales and deviations in the projection. As for the satellite images the only available data was Google Earth, which is limited in resolution and also turned out to be hard to geo-reference with high precision. However it was still useful in some operations like definition of areas affected by conservation practices.

An example of a major generalization is displayed in the C-factor for both catchments; all agricultural land was classified as crop-fallow rotation and assigned an average value for the entire class. Thus, this generalization is necessary since the model is for long term conditions and the distribution of cropped and fallow land changes on an annual basis.

In the original Whichmeier approach it is stated that the rainfall data record should be from a 20 years period minimum. In this case, data was only available over eight (Mrichet) and four (Sadine2) years respectively. The requirements of data are in general very low in this approach; however it would of course be desirable to fulfill the requirements as they are defined in the original approach.

The main tool in the calibration was the grid cell size, affecting the LS-factor layer mainly. Every new grid cell dimension required a new interpolation of the DEM into a raster layer of slope. This interpolation is very much of a great importance of the model outcome. Obviously the LS-factor values then are very dependent on the algorithm making this interpolation, why it could be of great interest to go deeper into the software routine of this operation. In addition to the generalizations of the slope raster layer generation there was also the slope length estimation. It was not possible to determine every single slope length so a fixed value was used. To neutralize the influence of the slope length, which was unknown for all slopes, the original 22m length was assumed (the length Whichmeier used in his original experimental plots when empirically developing the USLE).

Apart from the work on the grid cell size and the LS-factor a sensitivity analysis was performed on the other parameters. By changing parameter values one at the time it was possible to see how the estimated erosion was affected. However, the model equation is a simple multiplication of the parameters, why the sensitivity of every parameter is linear – a duplication of any parameter value would directly lead to a duplication of the estimated soil erosion.

The limitations of the USLE are mentioned in the literature review (chapter *2.3.2. Limitations*) and it is clearly stated that the model only estimates rill and inter-rill erosion. This means that no wind erosion is taken in consideration for the simulation. However this kind of erosion is not necessarily deposited in the reservoir in which the comparative values used in the calibration are estimated. Therefore wind erosion contribution is probably not included in the observed comparative values.

One of the main limitations of the USLE/GIS concept could be the absence of mass-, channel- and gully erosion in the simulation. The estimated erosion is very much too low and this may very well be because of the exclusion of mass-, channel and gully erosion in the model. As seen in *Figure 28,* mass erosion is acting on the catchments. The comparative values observed as siltation in the catchment reservoir therefore probably originate from other kinds of water erosion in addition to the contribution from rill and inter-rill erosion.

Figure 28; ***Not taking mass erosion in consideration is possibly one of the factors that causes the model to give unsatisfying results.***

5.2. Conclusion

The methodology as used in this approach does not seem to be applicable for semi-arid conditions. The result of simulated erosion is very much too low in comparison with the observed records of siltation, reaching only approximately 12-16 % of the observed values, depending on which grid cell size is used. There may be several reasons why, but as discussed in chapter *'3.2.3. Calibration'* it is hard to change the values of C-, P- and K- factors without redefining them. However the K-factor values are possibly underestimated for these regions; the USLE is originally not developed and defined under semi-arid conditions.

Also the R-factor seem to be underestimated; in other studies the R-factor is often several or even up to fifty times as high (Jain et al. 2010, Beskow et al. 2009) - however it is important to remember that the precipitation is also more intense in these regions.

The method could possibly be improved by redefining the K- and R-factor determination for semi-arid conditions. If adaptation to semi-arid conditions could be done, the USLE/GIS-approach can be a very powerful and available tool when predicting soil loss. In general the approach is very much available since restrictions in data easily can be overcome by approximations. Also the input data does not require a very high level of details, which makes it very applicable when data is insufficient. An idea could also be to determine the proportion of the comparative observed values that are represented by rill and inter-rill erosion and thereby have a more accurate and realistic comparative value for the calibration.

References

Literature and Articles

Beskow S., C. R. Mello, L. D. Norton, N., Curi, M.R. Viola, J.C. Avanzi, Soil erosion prediction in the Grande River Basin, Brazil using distributed modelling, *National Soil Erosion Research Laboratory, Purdue University, USA,* 2009.

Convention CES/IRD, Albergel, J., Pépin, Y., Boufaroua, M., et al, Annuaire Hydrologique des lacs Collinaires 1994-1995 … 2000-2001, *Direction de la Conservation Des Eaux et des Sols and Institut de Recherche pour le développement, Tunisia,* 1996-2002.

Dangler E. W., El-Swaify S. A., Ahuja L. R., Barnett A. P., Erodibility of selected Hawaii soils by rainfall simulation, *Agricultural research service, US department of agriculture, western region,* 113 p., 1976

Erdogan H. E., Erpul G., Bayramin I.: Use of USLE/GIS Methodology for Predicting Soil Loss in a Semiarid Agricultural Watershed, *Department of Soil SIence, University of Ankara, Turkey,* 2006

Fistikogli, O., Harmancioglu, N. B.: Integration of GIS with USLE in Assessment of Soil Erosion, *Faculty of Engineering, Dokuz Eylul University, Izmir, Turkey,* 2002

Jain Manoj K., Mishra Surendra K., R B Shah: Estimation of sediment yield and areas vulnerable to soil erosion and deposition in a Himalayan watershed using GIS, *Dep. Of Hydrology, Indian Institute of Technology, India,* 2010

Jankauskas, B., Jankauskiene, G., Fullen, M. A., Relations between soil organic matter content and soil erosion severity in Albeluvisols of the Žemaičiai Uplands, *Kaltinenai Research Station of the Lithuanian Institute of Agriculture, Lithuania,* 2007.

Jebari, S., Berndtsson, R., Bahri, A., Boufaroua, M.: Exceptional Rainfall Characteristics Related to Erosion Risk in Semiarid Tunisia, *National Research Institute for Rural Engineering, Waters and Forestry, Ariana, Tunis, Tunisia,* 2008.

Jebari, S.: Water erosion modeling using fractal rainfall disaggregation – A study in semiarid Tunisia, *Water resources engineering, Lund University, Sweden,* 2009.

Jebari, S., Berndtsson, R., Bahri, A., Boufaroua, M.: Spatial soil loss risk and reservoir siltation in semi-arid Tunisia, *Hydrological Siences Journal, 55:1, 121-137,* 2010.

Larsson, K., Harrie, L., Introduktion till GIS – Geografiska Informationssystem, *Institutionen för naturgeografi och ekosystemanalys & GIS-centrum, Lunds Universitet, Lund, Sweden,* 2005.

Masson, J.M.: Lérosion des sols par l’eau en climat Méditerranéen. Méthodes expérimentales pour l’étude des quantities érodées a l’échelle du champ Thése de Docteur-Ingénieur, *USTL Montpellier*, 1971

Moore, I. and Burch, G., Physical basis of the length-slope factor in the universal soil loss equation. *Soil Sci. Soc. Am. J.*, 1986a.

Moore, I. and Burch, G., Modeling erosion and deposition: topographic effects. *Trans ASAE*, 1986b

Moore, I. and Wilson, J. P., Length slope factor for the revised universal soil loss equation: simplified method of solution. *J. Soil Water Conserv*., 1992

Morgan, R.P.C., Davidson D. A.: Soil Erosion and Conservation, *Longman Group, U.K,* 1991.

OMM/WCP/M. C. Babau, La pluie et son agressivite en tant que facteur de l'erosion, *Organisation Metrologique Mondiale / World Climate Programme,* 1983.

Onyando J. O., Kisoyan P., Chemelil M. C.: Estimation of Potential Soil Erosion for River Perkerra Catchment in Kenya, *Department of Agricultural Engineering, Egerton University, Njoro Kenya*, 2004

Programme D'actions prioritaires, DIRECTIVES pour la cartographie et la mesure des processus d'érosion hydrique dans les zones côtières méditerranéennes, *Programme D'actions prioritaires, Croatia,* 1998

Strahler A., Strahler A.: Introducing Physical Geography, 3rd edition, *John Wiley & Sons inc., USA,* 2003.

Toy, J. T., Foster, R. G, Renard, K. G.: Soil Erosion – Processes, Prediction, Measurement and Control, *John Wiley & Sons inc., USA,* 2002.

Zante P., Collinet J., Leclerc G.: Cartographie des risques érosifs sur le basin versant de la retenue collinaire d'Abdessadok (nord dorsale tunisienne), *Institut de Recherche pour dèveloppement, Tunisia,* 2001

Ward R. C., Robinson M.: Principles of Hydrology, 4th edition, *McGraw-Hill Publishing Company, England*, 2000.

Whichmeier, W.H., and Smith, D.D: Predicting rainfall erosion losses – A guide to conservation planning. *USDA Agriculture Handbook 537*, Washington DC: GPO 1978

Wu, S.; Li, J., Huang, G.: An evaluation of grid size uncertainty in empirical soil loss modeling with digital elevation models, *Department of Agriculture, Regina, Saskatchewan, Canada,* 2005.

Online

FAO 1990: The conservation and rehabilitation of African lands -an international scheme, Food and Agriculture Organization of the United Nations, 1990. [online] accessed 2010-02-10
http://www.fao.org/docrep/z5700e/z5700e00.htm#Contents

FAO 1996: Land husbandry - Components and strategy, Food and Agriculture Organization of the United Nations, 1996. [online] accessed 2010-03-11
http://www.fao.org/docrep/t1765e/t1765e00.htm#Contents

Ministerè de l'agriculture et des resources hydrologiques, Tunisia, [online] accessed 2010-04-13
http://www.carteagricole.agrinet.tn/WEB/Produits/MCD/dd.htm#_Toc9840552

Stone & Hilborn, 2000: FACTSHEET, Universal Soil Loss Equation, Ministry of Agriculture, Food and Rural Affairs, 2000, [online] accessed 2010-03-11
http://www.omafra.gov.on.ca/english/engineer/facts/00-001.htm#background

USDA/NSERL: USLE Database, United States Department of Agriculture /National Soil Erosion Research Laboratory, [online] accessed 2010-03-11
http://topsoil.nserl.purdue.edu/usle/page7.html

Figures

Columbia University, 2008: *Hjulström diagram*, [online] accessed 2010-03-12
http://eesc.columbia.edu/courses/ees/lithosphere/homework/hmwk2.gif

Convention CES/IRD, *Direction de la Conservation Des Eaux et des Sols* and *Institut de Recherche pour le développement, Tunisia* 1998

FAO, 1996b, *K-factor determination,* [online] accessed 2010-05-20
http://www.fao.org/docrep/t1765e/t1765e0f.htm#soil erodibility

Fistikogli, O., Harmancioglu, N. B.: Integration of GIS with USLE in Assessment of Soil Erosion, *Faculty of Engineering, Dokuz Eylul University, Izmir, Turkey,* 2002

Jebari, S.: personal e-mail communication, 2009.

Larsson, K. and Harrie, L., Introduktion till GIS – Geografiska Informationssystem, *Institutionen för naturgeografi och ekosystemanalys & GIS-centrum, Lunds Universitet, Lund, Sweden,* 2005.

Other

Larsson, K.: Information from email correspondence concerning overlay operations of GIS-raster layers with different grid cell resolutions, *Institutionen för naturgeografi och ekosystemanalys & GIS-centrum, Lunds Universitet, Lund, Sweden.*, 2010-05-06.

Appendix A – R-factor

R-factor calculation; example

The R-factor was determined according to the original Wischmeier approach as described by OMM/WCP (1983). The example displayed here is the determination of R_{30} for an event recorded in the Mrichet catchment, dated to 28 Mars 1999. The event depth is 20 mm and duration is 5 h 15 min.

Table A1 shows the values of the calculation and the procedure is explained in the steps below.

Table A1; ***Calculation example for determination of R-factor.***

i	time	P_{ac} (mm)	P_s (30min)	I_s (mm/h)	I_{max} (mm/h)	e	E	E_{tot}	R
1	14:30	0	0	0	9	-	-	362,684	4,765191
2	15:00	2,5	2,5	5		18,00201	45,00502		
3	15:30	5	2,5	5		18,00201	45,00502		
4	16:00	9,5	4,5	***9***		20,23054	91,03742		
5	16:30	12,5	3	6		18,69326	56,07978		
6	17:00	15,5	3	6		18,69326	56,07978		
7	17:30	17,25	1,75	3,5		16,64971	29,137		
8	18:00	19,167	1,917	3,834		16,99528	32,57996		
9	18:30	19,605	0,438	0,876		11,39806	4,992351		
10	19:00	19,763	0,158	0,316		7,532268	1,190098		
11	19:30	19,921	0,158	0,316		7,532268	1,190098		
12	19:45	20	0,079	0,158		4,904276	0,387438		

Calculation procedure;

- $\mathbf{P_{ac}}$ is accumulated rainfall depth, recorded in field
- $\mathbf{P_s}$ is the rainfall depth of each 30-min segment ($P_{ac,\,i}$ - $P_{ac,\,i\text{-}1}$)
- $\mathbf{I_s}$ is the rainfall intensity of each 30-min segment ($P_s \cdot 2$)
- $\mathbf{I_{max}}$ is the maximum intensity determined from column I_s
- **e** is the kinetic energy / mm of each 30-min segment, determined by eq. X1
- **E** is the kinetic energy of every 30-min segment ($e_i \cdot P_{s,\,i}$)
- $\mathbf{E_{tot}}$ is the sum of E for the entire event
- **R** is the event R-factor determined by eq. X2

Note that the last segment *i*=13 is insufficient in time period. The segment intensity I_s is still calculated by multiplication by two, as proposed for events with duration less than 30 minutes (OMM/WCP, 1983). The total annual R-factor is then equal to the sum of all events within the year and finally annual averages are determined.

$e = 8{,}73 \cdot \log I_s + 11{,}9$ eq. X1

$R = \frac{E_{tot} \cdot I_{max}}{685}$ eq. X2

Valid events and determined R-factors

Table A2 shows the 55 valid rainfall events of Mrichet catchment in the period 1993-09-24 to 2002-09-25 (P = mm, duration = hh:mm, I = mm/h);

Table A2; ***The valid rainfall events of Mrichet***

Year	Month	Day	Nr	P	Duration	I_{15}	I_{30}	R_{15}	R_{30}	Hydr. Yr	R_{15}	R_{30}
1994	Jan	8	1	18	02:55	12	10	5,968684644	4,953939			
	Sep	9	2	18	01:30	76	65	217,3408274	185,1979			
	Sep	27	3	73	07:25	20	16	9,671233938	7,660493			
	Oct	3	4	28,5	04:05	58	38	57,59423271	37,01169			
1995	Mar	12	5	14	06:00	6	6	7,846365354	3,906067	1994/1995	292,5	233,8
	Sep	20	6	16,5	00:35	40	20	94,81395527	21,78923			
	Sep	22	7	14,5	01:00	47,33	25,67	99,08499426	25,33283			
	Sep	24	8	16	00:20	50	32	119,9474581	37,432			
	Nov	2	9	24,5	03:10	24	14	69,7924028	19,76258			
1996	Jan	11	10	24	10:25	10	7,33	5,590560246	4,071428			
	Jan	13	11	27,5	10:35	6	6	3,862971091	3,832277			
	Feb	7	12	15	06:00	7	4,5	2,407591845	1,520114			
	Feb	8	13	20,5	06:40	8	8	4,022177024	3,938873			
	Feb	27	14	23,5	09:10	6	4,67	3,209964139	2,458159			
	Feb	27	15	16	11:20	4	3,17	1,261929825	0,988085			

	Mar	14	16	19,5	04:05	12	11,5	6,237775813	5,890872			
	Apr	29	17	13	04:00	10	9	3,343824947	3,002113			
	May	10	18	52,5	03:05	58	36	109,3898416	66,44242			
	Aug	14	19	16	00:55	38	21	21,19453004	11,00227	1995/1996	544,2	207,5
	Sep	9	20	33,5	03:00	56	38,5	65,12305478	44,01919			
	Sep	16	21	24,5	01:15	44	38	38,28943198	32,63285			
1997	Jan	25	22	13	05:40	6	5	1,811550875	1,483335			
	Apr	9	23	41,5	16:25	6	6	5,992459941	5,97816			
	Jun	1	24	28,5	01:10	48	28,5	50,04636928	27,87528	1996/1997	161,3	112
	Sep	6	25	13	01:45	22	12,5	8,605089183	4,690256			
	Oct	5	26	50,5	02:25	42	35	74,37523252	61,50293			
	Oct	13	27	14,5	00:55	34	20	16,91576344	9,448681			
	Nov	12	28	16	04:55	8	6	3,254890914	2,375777			
	Nov	23	29	26,5	06:20	14	11	10,32224852	8,077637			
	Dec	23	30	20	08:30	7	6	3,264808034	2,787771			
1998	Feb	27	31	13,5	06:10	10	7,5	3,222270539	2,382566			
	Jun	6	32	18	01:20	37	31,17	23,08370213	19,35898	1997/1998	143	110,6
	Sep	23	33	52,5	05:25	26	17	42,43581205	27,44091			
	Oct	10	34	16,5	06:00	8	5,5	3,164036719	2,153025			
	Nov	28	35	13	06:25	6,4	4	1,836364805	1,125255			
1999	Jan	17	36	16	09:30	5,33	3,83	1,887319865	1,325646			
	Jan	19	37	56	18:05	10	7	14,02840351	9,714972			
	Mar	28	38	20	05:05	12	9	6,423106801	4,765191			
	May	8	39	15	04:05	10	8	3,945457521	3,119766			
	Jun	4	40	19,5	00:20	74	39	58,24893824	28,63254	1998/1999	132	78,28
	Sep	9	41	23	02:00	30	18	22,64438295	13,06464			

	Nov	27	42	55,5	14:15	16	10,5	23,62485923	15,35133			
	Nov	28	43	16	02:30	16	12,33	7,784804383	5,897444	1999/2000	54,05	34,31
2000	Sep	12	44	22	01:45	34	28	25,1137981	20,29682			
	Sep	12	45	32,5	02:20	34	19,33	37,18074812	20,46022			
	Sep	27	46	17,5	01:35	48	30	29,44484585	17,88713			
	Sep	28	47	15,5	02:30	19,6	11	8,824887624	4,782631			
	Okt	20	48	15,5	03:55	18	11	7,621159189	4,52708			
	Okt	21	49	5,5	06:45	22	12,25	20,8373352	11,08866			
2001	May	4	50	25,5	07:00	8	7	5,226950783	4,536584			
	May	11	51	26,5	10:55	10	9	6,423536953	5,753429	2000/2001	140,7	89,33
	Sep	29	52	27	00:40	58	50	60,03945188	51,28556			
2002	Mar	17	53	17	02:45	30	21	15,87114392	10,89728			
	Mar	17	54	29	04:05	12	9	10,00770398	7,419273			
	May	7	55	14,5	00:35	32	20	16,01172583	9,448681	2001/2002	101,9	79,05

Table A3 shows the 30 valid rainfall events of Sadine2 catchment in the period 1994-03-24 to 1998-09-16 (P = mm, duration = hh:mm, I = mm/h);

Table A3; ***The valid rainfall events of Sadine2***

Year	Month	Day	Nr	P	Duration	I_{15}	I_{30}	R_{15}	R_{30}	Hydr. Yr	R_{15}	R_{30}
1994	Apr	16	1	20	03:20	16	13,29	9,3093	7,6855			
	Jul	31	2	38	00:40	66	64	99,157	94,673			
1995	Jun	24	3	13,5	01:40	26	20,27	11,19	8,5369	1994/1995	110,3466	103,2104
	Oct	15	4	23	05:05	20	12	12,918	7,5852			
1996	Jan	30	5	15,5	08:15	5	4,5	1,7028	1,5251			
	Feb	7	6	17	09:20	6	3	2,1925	1,0864			

	Feb	8	7	20	06:00	10	6	5,0211	2,9692			
	Apr	29	8	15	05:20	8	8	3,0329	3,0139			
	May	10	9	18,5	03:30	36	24	21,614	13,99			
	Aug	8	10	16	00:15	50	32	29,987	18,716			
	Aug	15	11	25	00:45	44	35	40,617	31,188			
	Aug	17	12	13,5	00:20	32	27	15,427	12,981	1995/1996	132,511	93,05585
	Sep	9	13	24	00:55	42	25	36,723	20,98			
1997	Jan	11	14	64,5	22:10	10	7	15,713	10,916			
	Jan	12	15	20,5	12:10	6	4,67	2,6277	2,0194			
	Jan	26	16	19,5	07:45	6	5,5	2,8524	2,5818			
	Mar	15	17	14	09:45	8	5,4	2,4425	1,6131			
	Apr	24	18	14	03:30	8	8	2,9226	2,9031			
	May	17	19	17	00:40	44	33	27,357	20,283			
	Aug	5	20	15	00:55	42	23	22,05	11,451	1996/1997	112,6879	72,74749
	Sep	21	21	21	00:40	54	38	42,12	28,983			
	Nov	23	22	24	05:05	10	8	6,5543	5,2084			
	Dec	6	23	21	07:45	6	6	3,0512	3,0325			
	Dec	23	24	13,5	08:40	7	5	2,0354	1,4356			
1998	Feb	27	25	21,5	06:05	8	7	4,4003	3,8215			
	Mar	15	26	34	10:45	12	8	10,336	6,8062			
	Mar	30	27	14,5	04:25	12	10	4,6675	3,8411			
	Apr	22	28	13,5	05:30	5	4	1,5541	1,2315			
	May	16	29	13	03:25	13	10	4,5476	3,4678			
	Jun	6	30	15,5	00:45	50	28	28,484	15,025	1997/1998	107,7505	72,852

The R-factors were determined as averages;

- For the HY-period it was determined as the annual average from all data within the complete hydrological years; 8 for Mrichet, 4 for Sadine2.
- For the maximum and average period it was determined as the average regarding all available data within the given time period, also taking the incomplete calendar years in consideration.
-

Mrichet;

Period	R_{15}	R_{30}
HY-per.	196,2	118,1
Ave. per.	212,2	124,4
Max. per.	168	119

Sadine2;

Period	R_{15}	R_{30}
HY-per.	115,82	85,47
Ave. per.	105,49	78,02
Max. per.	71,17	62,84

The average annual precipitation was also determined for the hydrological years*;*

Mrichet;

HY yr	**P**
1994/1995	349,5
1995/1996	744,5
1996/1997	321,5
1997/1998	533
1998/1999	545
1999/2000	271,5
2000/2001	306,5

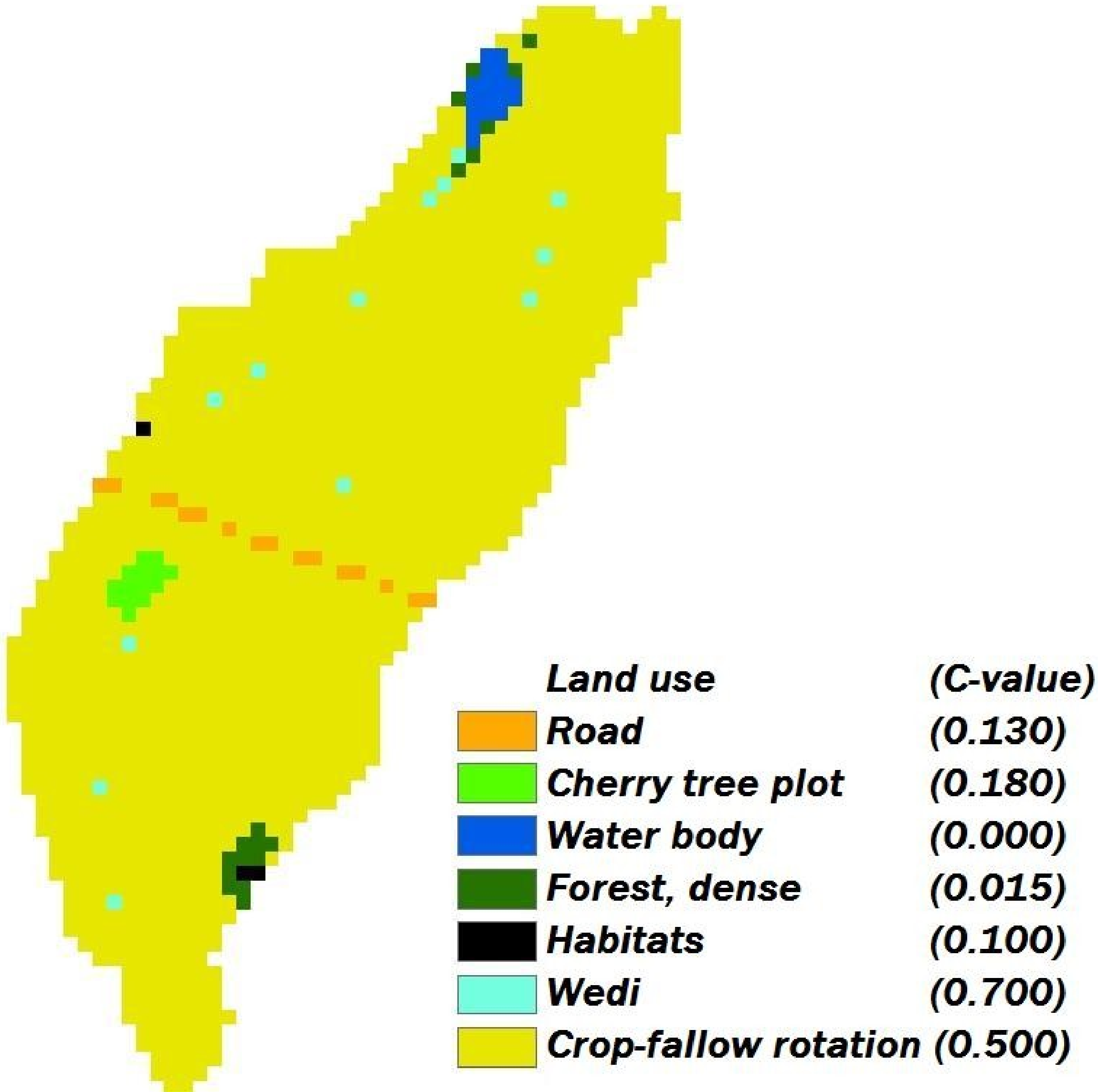
2001/2002	307,5
Average;	422,375

Sadine2;

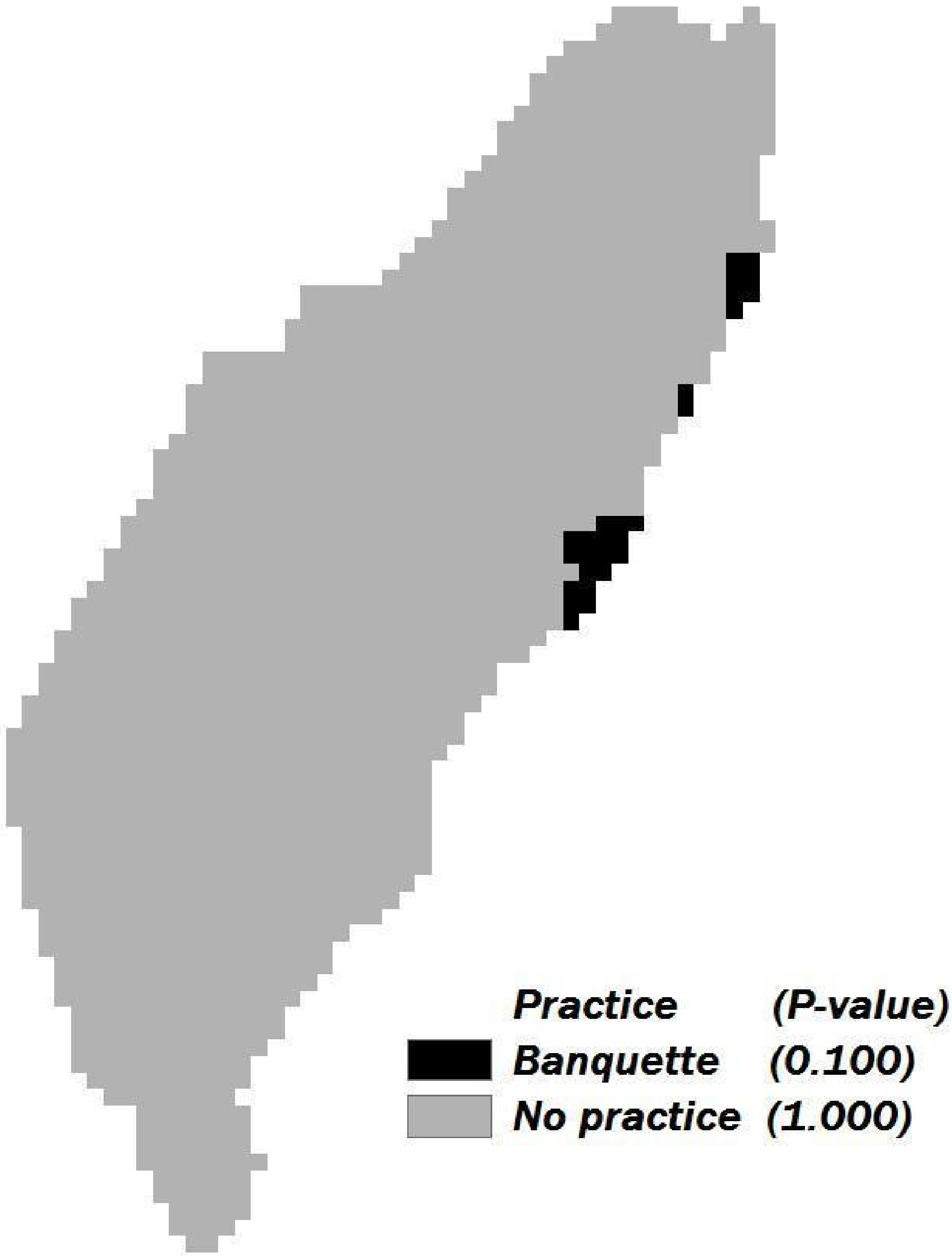
HY yr	**P**
1994/1995	242
1995/1996	589
1996/1997	426,5
1997/1998	501,5
Average;	439,75

Appendix B – Thematic layers

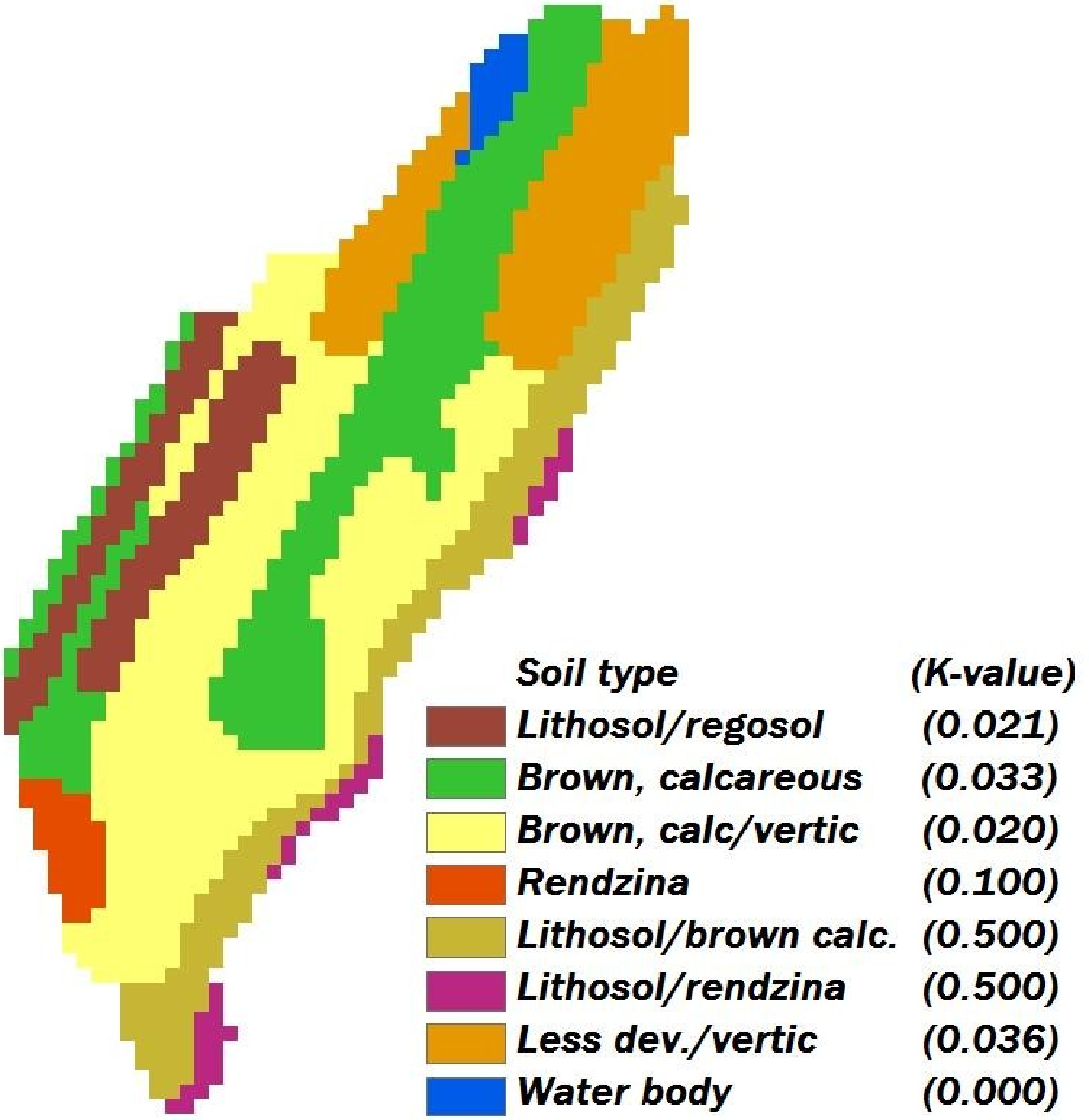
Mrichet – C-factor - Land use



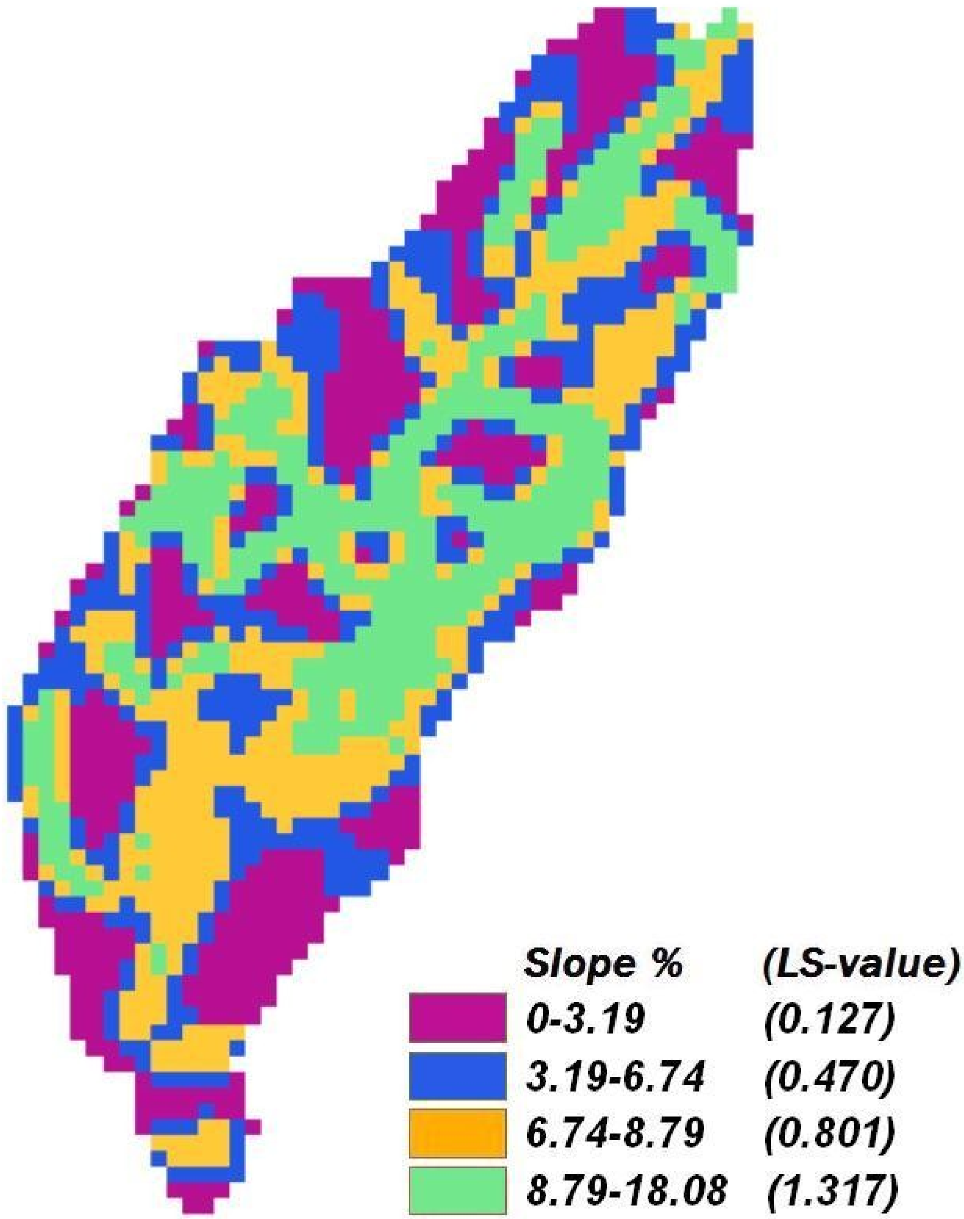
Mrichet – P-factor – Conservation practices



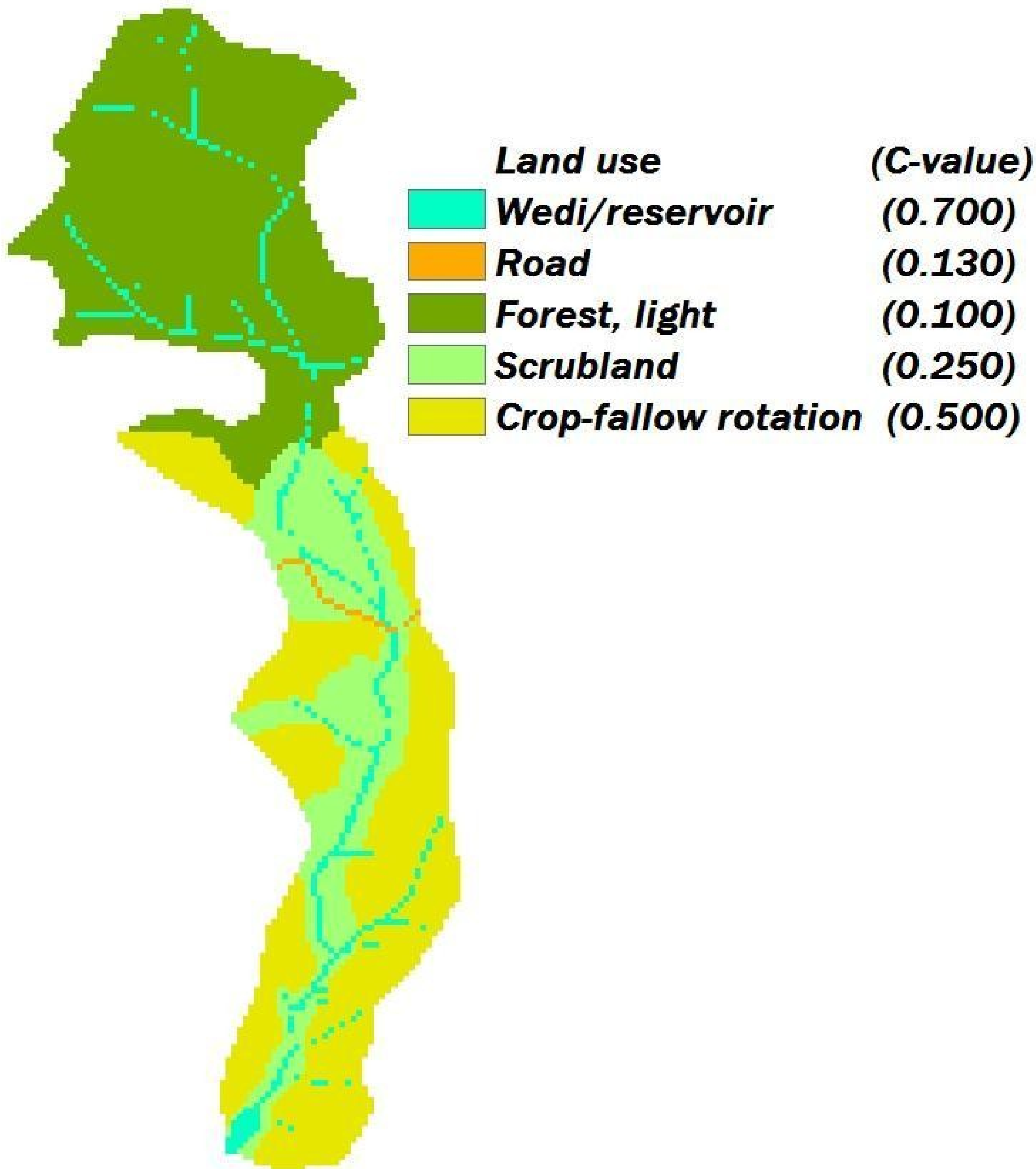
Mrichet – K-factor – Pedology



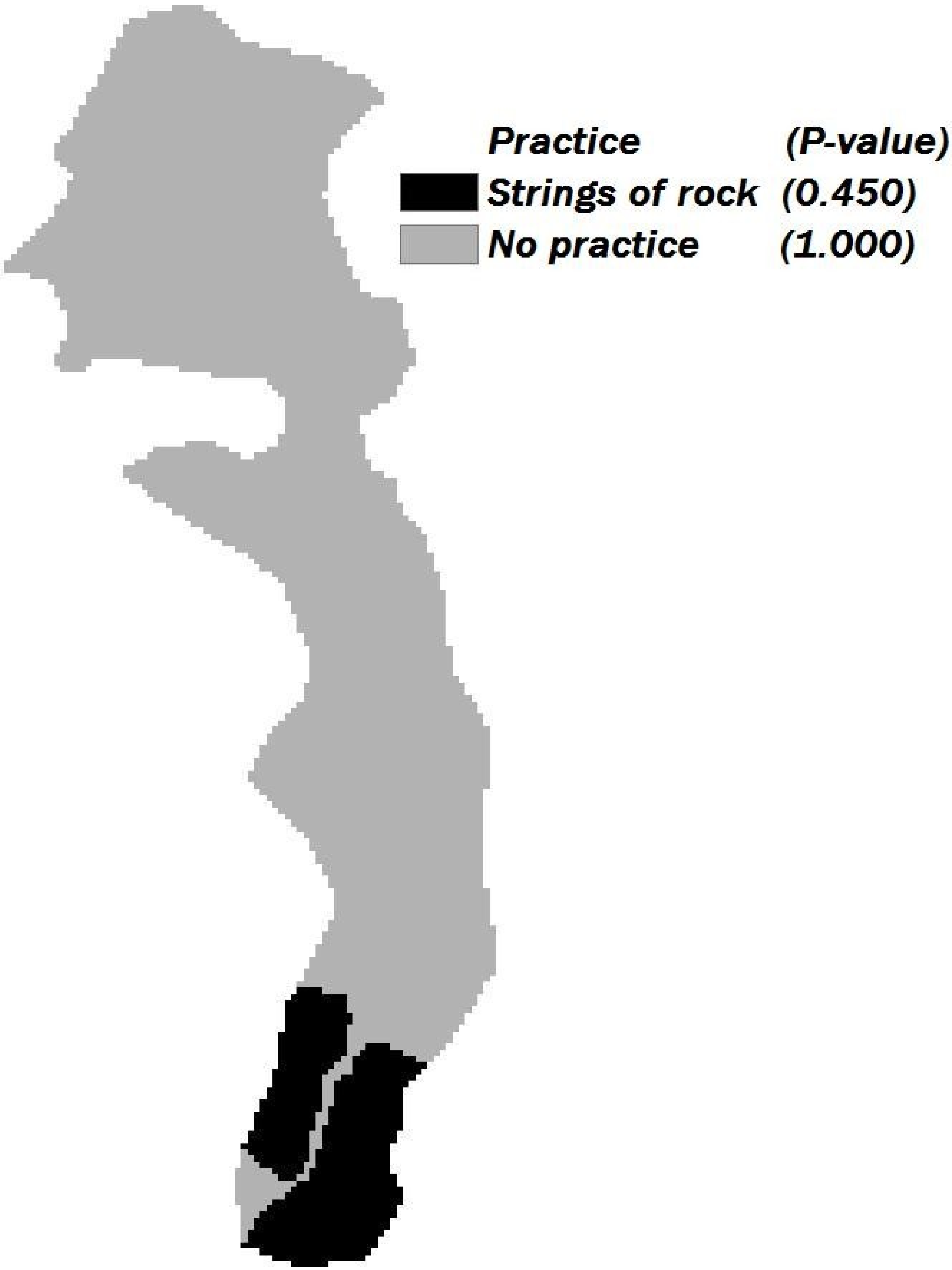
Mrichet – LS-factor – Topography



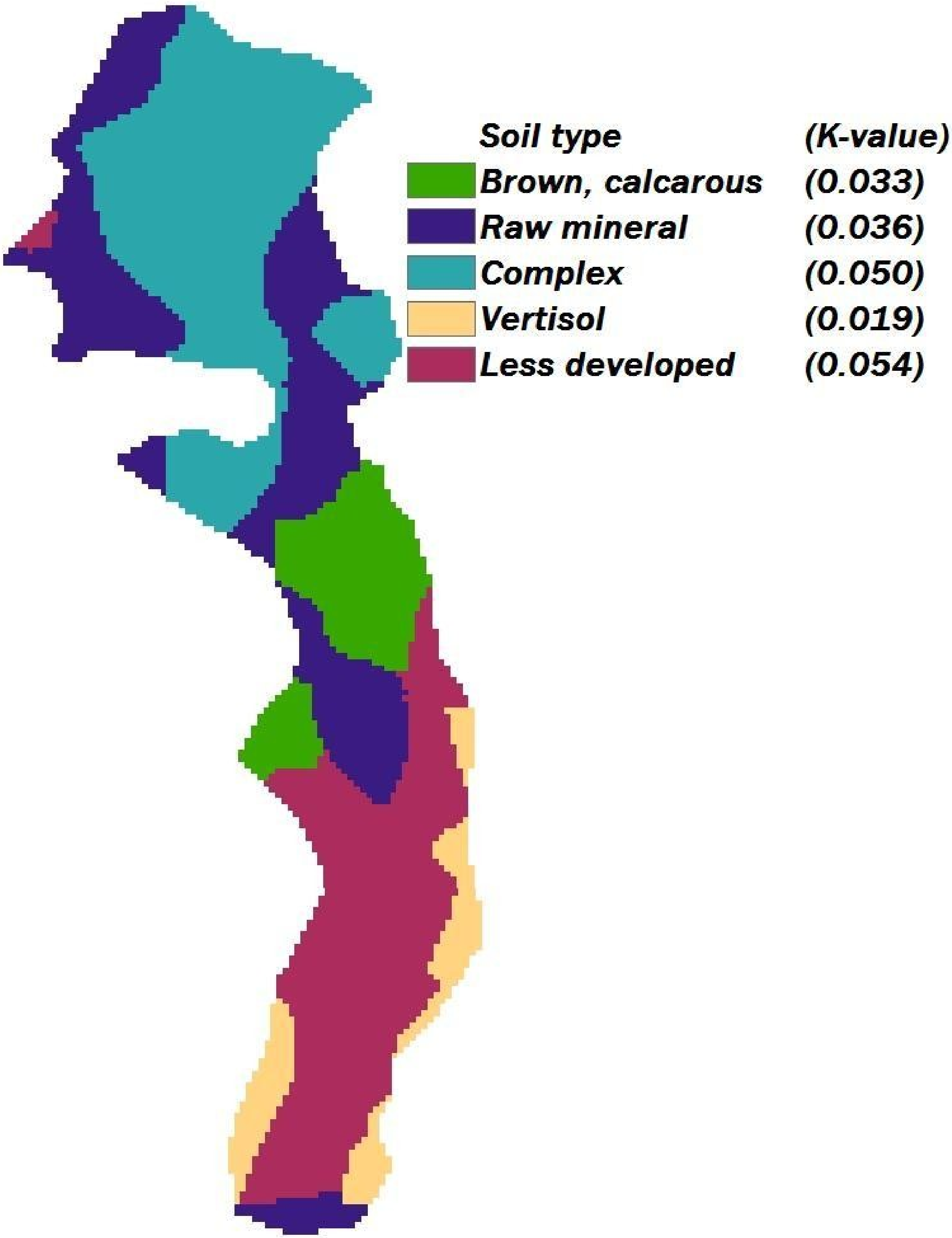
Sadine2 – C-factor - Land use



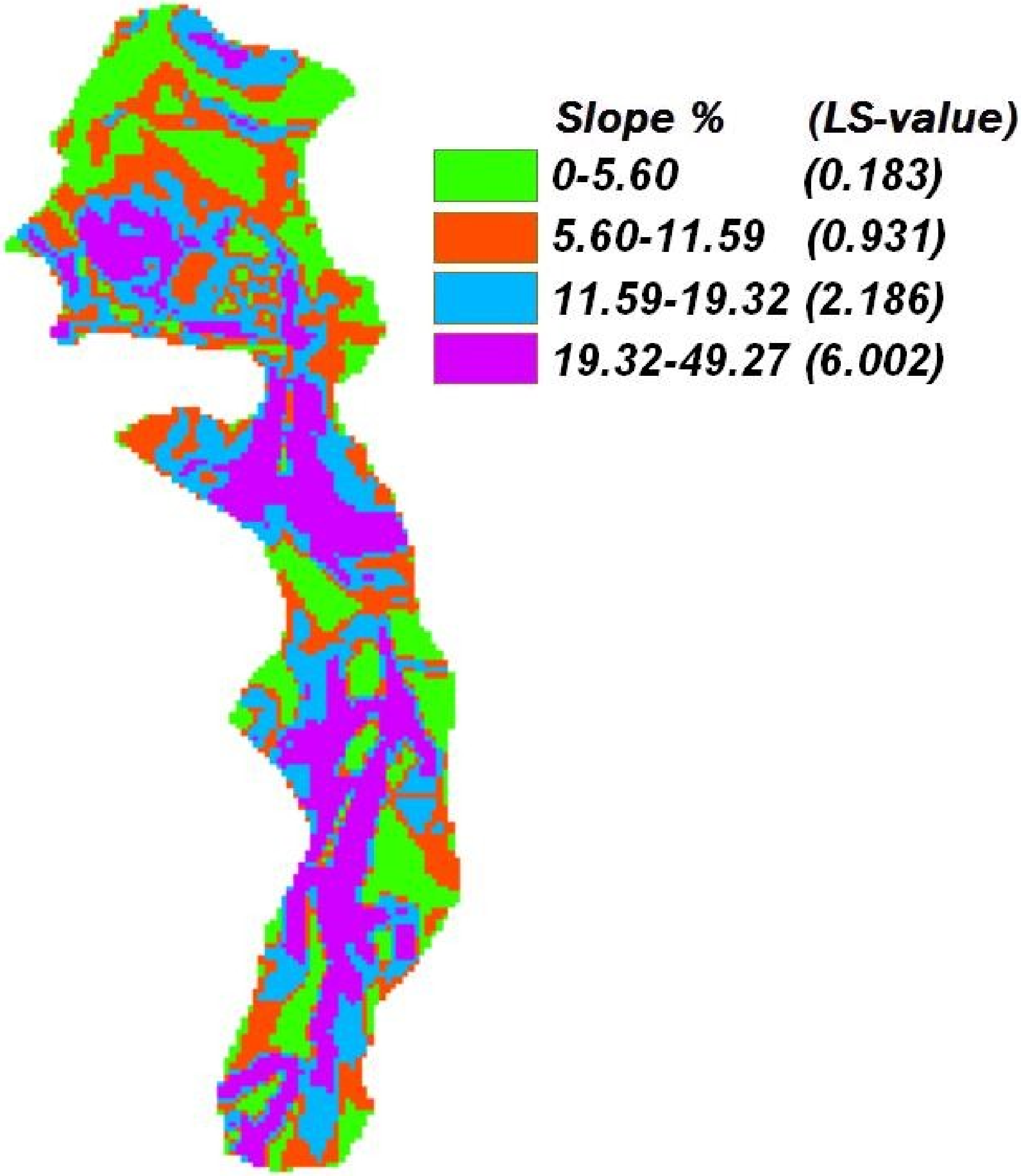
Sadine2 – P-factor – Conservation Practices



Sadine2 – K-factor – Pedology

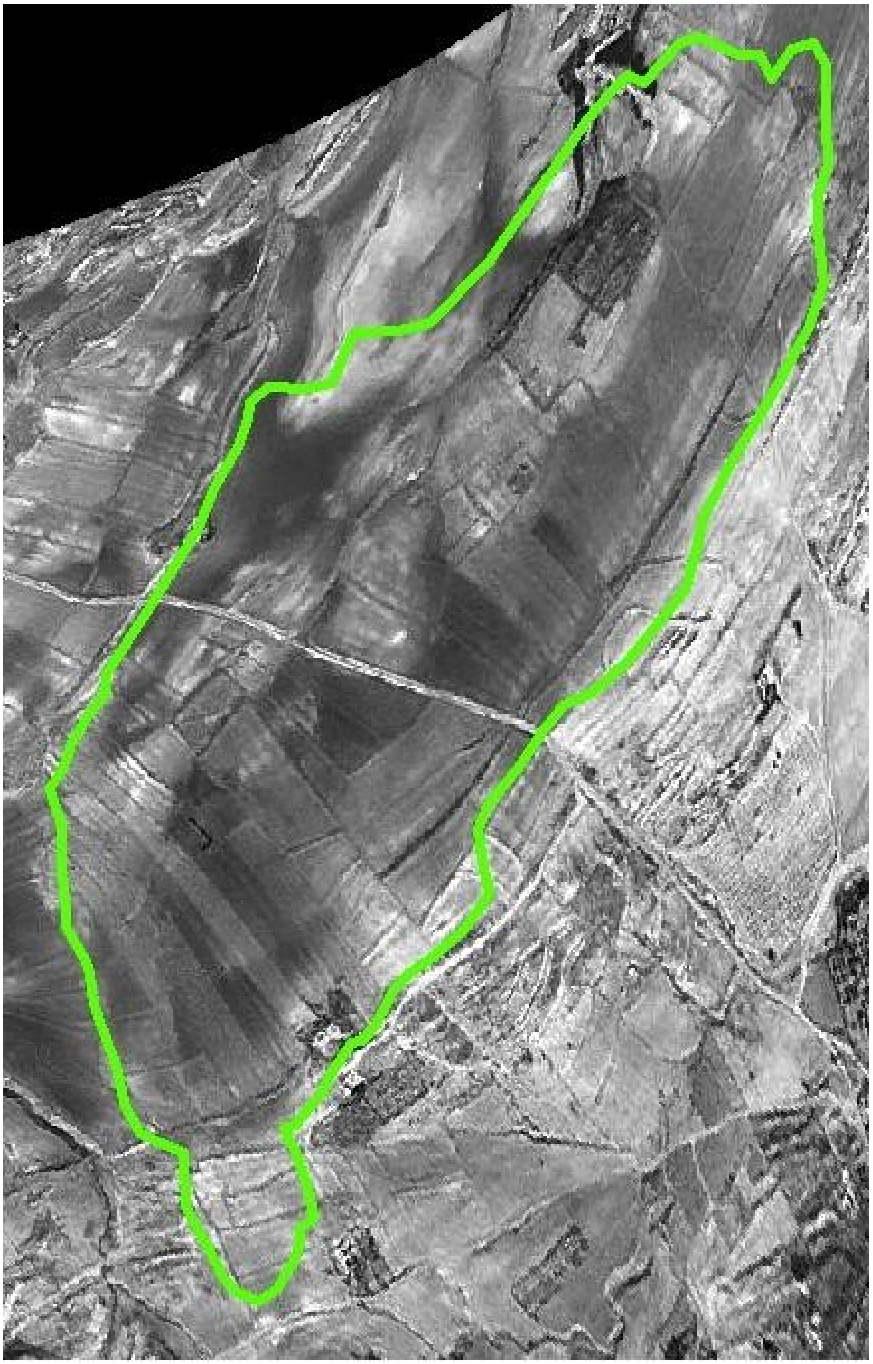


Sadine2 – LS-factor – Topography



Appendix C – Satellite Images

Mrichet



Sadine2