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ESTIMATION OF SOIL EROSION AND SEDIMENT YIELD USING THE GEOWEPP MODEL IN WADI EL MALLEH WATERSHED, MOROCCO.

By

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Master in ***Water, Engineering Track***

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Software used	
GeoWEPP ArcGIS 10.3	Google Earth

DECLARATION

I, **Christian NDAYEGAMIYE,** hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Christian NDAYEGAMIYE		**August, 2nd, 2018**
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ABSTRACT

Soil erosion is the most important soil degradation process in Morocco and a major environmental and economic concern that threatens the sustainability of dam reservoirs and agricultural lands. Moroccan soils face high erosion rates which exceed tolerable thresholds. In order to develop a comprehensive plan for soil and water conservation, it is crucial to describe the rate of soil erosion and sediment transport in the watershed over spatial and time scales. In this study, The GeoWEPP model was used for the first time in Wadi El Malleh watershed to glean useful information to guide soil conservation planning and management. The most susceptible soil units to erosion were identified along with the land use/management types associated with extremely high erosion rates. The analysis of onsite and offsite erosion assessment results across the different watershed allowed us to identify the most critical sub watersheds. The hillslopes dominated with the couple winter wheat, conventional till management/soil unit 15 (Vertisol) on the steepest slopes were associated to the highest erosion rates between 88.9 t/ha/yr and 135 t/ha/yr in the four sub watersheds identified as most critical and prioritized for soil conservation strategy assessment. A 90% reduction of soil loss rates was achieved by changing the hillslope land uses/management from winter wheat, conventional till to alfalfa with cuttings. Important insights that were gleaned from the use of GeoWEPP model in this study have the potential to increase the effectiveness of soil conservation planning in Wadi El Malleh watershed.

Key words: Soil erosion, onsite and offsite assessment, GeoWEPP model, soil conservation planning, Wadi El Malleh watershed, Morocco

RÉSUMÉ

L'érosion des sols est le processus de dégradation des sols le plus important au Maroc et une préoccupation environnementale et économique majeure qui menace la durabilité des réservoirs de barrage et des terres agricoles. Les sols marocains connaissent des taux d'érosion élevés qui dépassent les seuils tolérables. Afin de développer un plan global pour la conservation des sols et des eaux, il est crucial d'évaluer l'ampleur de l'érosion des sols et le transport des sédiments dans le bassin versant sur des échelles spatiales et temporelles. Dans cette étude, le modèle GeoWEPP a été utilisé pour la première fois dans le bassin versant d'Wadi El Malleh en tant que puissant outil d'aide dans la planification et la gestion de la conservation des sols. Les unités de sol les plus sensibles à la perte en terres ont été identifiées ainsi que les types d'occupation de sol associés à des taux d'érosion extrêmement élevés. L'analyse des résultats de l'évaluation de l'érosion et transport de sédiments dans les différents sous bassins versants nous a permis d'identifier les sous-bassins les plus touchés. Les versants où dominent le couple blé d'hiver (avec labour conventionnel) / unité de sol 15 (Vertisol) sur les pentes très fortes étaient associées aux taux d'érosion les plus élevés entre 88,9 t / ha / an et 135 t / ha / an dans les quatre sous-bassins identifiés comme les plus touchés et ayant été choisi comme zone pilote pour l'évaluation d'une stratégie de conservation des sols. Une réduction de 90% du taux moyen de perte en sol a été enregistrée en substituant le blé par la luzerne au niveau de tous les versants sélectionnés. Les observations importantes issues de l'application du modèle GeoWEPP dans le cadre de cette étude ont le potentiel d'accroître la pertinence de la planification des activités de conservation des sols dans le bassin versant de l'Wadi El Malleh.

Mots clés : Erosion du sol, transport de sédiments, modèle GeoWEPP, planification de la conservation du sol, bassin de l'Wadi El Malleh, Maroc.

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CHAPTER I: INTRODUCTION

I.1. Background.

Soil erosion is one of the most serious environmental and public health problems facing human society. Humans obtain more than 99.7% of their food (calories) from the land and less than 0.3% from the oceans and other aquatic ecosystems. Each year about 10 million ha of cropland are lost due to soil erosion, thus reducing the cropland available for food production. Overall soil is being lost from land areas 10 to 40 times faster than the rate of soil renewal imperiling future human food security and environmental quality. (Pimentel, 2006)

Soil erosion is the most important soil degradation process in Morocco, which affects up to 40% of its territory according to FAO (1990). Being at the same time a major environmental and economic problem that threatens the sustainability of dam reservoirs and agricultural lands in the Rif Mountains. The total annual soil loss is evaluated at 100 million tons which correspond to 50 million m^3 annual reduction in the storage capacity of the dams. (Ouassou et al., 2006 cited in Dahan et al., 2012).

In Morocco, Soil erosion is a consequence of increased population pressure and overexploitation of forestry resources. Moroccan soils face high erosion rates which exceed international standards. Removal of natural vegetation from the slope lands and their conversion for cultivation exposed many extensive areas of the mountains regions and plateaus to soil erosion. This is particularly the case of the Rif Mountain, which is characterized by steep and long slopes, soft geologic material (marl and shale), and severe climatic conditions. Erosion rate in the Rif Mountain is one of the most severe ones in the world (30 to 70 t/ha/year). Also, overgrazing and cultivation of vulnerable land in arid and desert regions have induced severe wind erosion. Soil degradation is enhanced by inappropriate land management, mainly tillage.

Tillage is one of the main degradation factors in the Mediterranean basin. Tilling up and down slope also produced a net soil transport in the direction of tillage and leads to soil degradation. (Dahan et al., 2012)

Around 35% of the Moroccan rural population live in areas of serious degradation. The rural poor heavily depend on forest resources, creating extra stress on ecosystems when rangelands and croplands are unable to meet and sustain their livelihoods. It is estimated that areas in the process of degradation affect the livelihoods and food security of about 1.5 million households in Morocco, who then further extend their agricultural production and livestock systems to other marginal and fragile lands, thus seriously further degrading the natural resource base. An economic analysis has estimated the global cost of lost productivity in Morocco as a result of land degradation at between USD 91 and 178 million per year (cropland and rangeland degradation). (Dahan et al., 2012)

I.2. Problem Statement and Justification of the Study.

Soil erosion and sedimentation continually threaten the sustainability of upland farming, the health of downstream ecology, and the quality and quantity of water resource (Puno, 2014). In order to develop a comprehensive plan for soil and water conservation, it is essential to estimate runoff and soil loss resulting from different crop and structure-based management practices.(Singh et al., 2011)

To some extent, quantitative information on soil loss magnitude and distribution is available for some watersheds in the Northern Morocco. Different studies (Chen et al. (2008); Elbouqdaoui et al. (2005);Iaaich et al. (2016) ; Khali Issa et al. (2016); Lahlaoi et al. (2015); Sadiki et al. (2009)) have combined GIS, remote sensing and Soil erosion empirical models namely USLE and/or RUSLE to estimate and map soil loss rates in the Rif and Pre-rif region including Wadi El Malleh catchment, our study area (El Aroussi et al., 2011; El Garouani et al., 2017).

However, no study has ever focused on offsite impact assessment of erosion because only empirical soil erosion models that cannot predict sediment delivery to the catchment Outlet (the total sediment load that leaves a drainage basin (usually measured in tons/ha/year) were used so far.

A number of physically based soil erosion hydrological models have been developed worldwide for prediction of soil erosion and sediment yield. Physically based spatially distributed models can be used to identify critical areas by providing the output at any desired location within the watershed with increased accuracy of simulation compared to empirical or conceptual models on top of performing a sediment routing within the watershed channel network allowing the user to predict the sediment yield from each sub watershed.

The GeoWEPP model used in this study is a physically based, continuous simulation computer program which predicts soil loss and sediment transport and deposition from overland flow on hillslopes, soil loss and sediment deposition from concentrated flow in small channels, and sediment deposition in impoundments (Fares, 2008 cited in De Mello *et al.*, 2016).

I.3. Research Objectives

The main objective of this study was to examine the use of the GeoWEPP model for conservation planning in Wadi El Malleh watershed.

The specific objectives were to:

i. Assess the susceptibility of different soil type and land use types to soil erosion
ii. Identify critical sub watersheds and understand erosion and sediment delivery processes at the watershed scale.
iii. Assess the effectiveness of a soil conservation strategy in the reduction of soil erosion magnitude.

I.4. Research Questions

Based on the stated objectives, the following questions have been used to guide the research process and finally answered from the findings of the study:

i. How is soil loss distributed in the watershed?
ii. Which soil and landuse type is associated with high soil erosion rates?
iii. Which sub watershed is the most affected with soil erosion and what are the main contributing factors?
iv. Which sub watershed is delivering much of its soil loss to the outlet and what are the main contributing factors?
v. How can the GeoWEPP model help in assessing the effectiveness of a soil conservation practice in reducing the magnitude of soil loss and sediment yield at the watershed scale?

CHAPTER II: LITERATURE REVIEW

II.1. Soil erosion impact in managed ecosystems

Approximately 50% of the earth's land surface is devoted to agriculture; of this, about one-third is planted to crops and two-thirds to grazing lands (USDA, 2001). Forests occupy about 31% of the land area (WRI, 1996). Of these two areas, cropland is more susceptible to erosion because of frequent cultivation of the soils and the vegetation is often removed before crops are planted. This practice exposes the soil to wind and rain energy. In addition, cropland is often left without vegetation between plantings. This practice intensifies erosion on agricultural land, which is estimated to be 75 times greater than erosion in natural forest areas (Myers, 1993 cited in Pimentel, 2006).

Erosion on cropland averages about 30 t/ha-yr and ranges from 0.5 to 400 t/ha-yr worldwide (Pimentel et al., 1995). As a result of soil erosion, a large portion of the world's arable land become unproductive year after year and, much of that is abandoned for agricultural use. (Pimentel, 2006)

Worldwide, soil erosion losses are highest in the agroecosystems of Asia, Africa, and South America, averaging 30–40 t/ha-yr of soil loss (Taddese, 2001). In developing countries, soil erosion is particularly severe on small farms that are often located on marginal lands where the soil quality is poor and the topography is frequently steep. In addition, the poor farmers tend to raise row crops, such as corn. Row crops are highly susceptible to erosion because the vegetation does not cover the entire soil. (Pimentel, 2006)

Almost all Moroccan lands face water erosion and more than 2 million hectares of agricultural lands are water eroded. Average soil degradation varies from 2.1 to 20 t/ha/year, but exceeds these rates in northern and north-western basins.

In the pre-Rif hills, measured erosion in small basins is about 5.8 t/ha/year for a forested watershed, 18.4 t/ha/year for a mixed-use basin (cleared and cultivated), and over 90 t/ha/year in fully cultivated basins. Until year 1988, 700 million m^3 storage capacity was lost, and it is appraised that the actual annual loss of 50 million m^3 capacity will rise to 150 million m^3 in about year 2030, if siltation is not confined (Anon, 1995). As a comparison, the storage capacity loss is evaluated at 0.5 to 1% per year in the Mediterranean circumference, whereas it is 2% in Morocco. (Dahan et al., 2012)

II.2. Factors of erosion

Erosion occurs when soil is left exposed to rain or wind energy. Raindrops hit exposed soil with great energy and easily dislodge the soil particles from the surface. In this way, raindrops remove a thin film of soil from the land surface and create what is termed sheet erosion. This erosion is the dominant form of soil degradation (Troeh et al., 1991; Oldeman, 1997 cited in Pimentel, 2006). The impact of soil erosion is intensified on sloping land, where often more than half of the surface soil is carried away as the water splashes downhill into valleys and waterways.(Pimentel, 2006)

II.2.1. Soil Structure

Soil structure influences the ease with which it can be eroded. Soils with medium to fine texture, low organic matter content, and weak structural development are most easily eroded (Bajracharya & Lal, 1992). Typically these soils have low water infiltration rates and, therefore, are subject to high rates of water erosion.

II.2.2. The Role of Vegetative Cover

Land areas covered by plant biomass, living or dead, are more protected and experience relatively little soil erosion because raindrop are dissipated by the biomass layer and the topsoil is held by the biomass (Agriculture California, 2002; SWAG, 2002 cited in Pimentel, 2006).

In forested areas, a minimum of 60% forest cover is necessary to prevent serious soil erosion and landslides (Singh & Kaur, 1989).The extensive removal of forests for crops and pastures is followed by extensive soil erosion.

Loss of soil vegetative cover is especially widespread in developing countries where populations are large, and agricultural practices are often inadequate to protect topsoil. In addition, cooking and heating there frequently depend on the burning of harvested crop residues for fuel. All these practices leave the soil barren and fully exposed to rain and wind forces of erosion.(Pimentel, 2006)

II.2.3. Land Topography

The topography of a given landscape, its rainfall and/or wind and exposure all combine to influence its susceptibility to erosion. In the Philippines, where more than 58% of the land has a slope of greater than 11%, and in Jamaica, where 52% of the land has a slope greater than 20%, soil erosion rates as high as 400 t/ha-yr have been reported (Lal & Stewart, 1990). Erosion rates are high especially on marginal and steep lands which have been converted from forests to agriculture to replace the already eroded, unproductive cropland (Lal & Stewart, 1990).

II.3. Erosion Models

Quantitative results related to the soil loss rates and conservation strategies are not usually available for areas with erosion problems. However, quantitative erosion assessments and possible strategies for management of basins are necessary for both local planning and governmental agencies associated with sustainable development. (De Roo & Jetten, 1999)

Among the available tools for soil erosion assessment, simulation models are quite important because appropriate models can be used to evaluate a variety of management scenarios without costly and time-consuming field tests (Pieri et al., 2007).

GIS-based spatial modeling has emerged as an important tool in soil erosion studies and consequently in the development of appropriate soil conservation strategies, especially at the watershed scale (Memarian et al., 2012 cited in Reza Meghdadi, 2013).

Several quantitative models have been proposed to date for rainfall induced soil erosion. These models can be grouped into three main categories: empirical, conceptual and physically based models.(Cuomo et al., 2015)

II.3.1. Empirical Models

Empirical models usually establish relationships between runoff, sediment yield and precipitation, plants, soil types, land use types, tillage styles, water conservation measures and so on. They are still used because of their simple structure and ease of application. Since they are based on coefficients computed or calibrated from measurements and/or observations, they cannot describe or simulate the erosion process as a set of physical phenomena. The Universal Soil Loss Equation (USLE) is the most widely used empirical erosion model. It is used to estimate soil erosion from an area simply as the product of empirical coefficients, which must therefore be accurately evaluated. Original values of coefficients were derived from field observations in different areas of the eastern U.S., but they have been expanded with time using information from researchers who have applied the USLE (and derived models) in other countries. (Shen et al., 2009)

II.3.1. Conceptual Models

In conceptual models, a catchment is represented as a series of internal storages. Without including the specific details of process interactions, which require detailed catchment information, the model tends to include a general description of catchment processes (Sorooshian, 1991). Parameters of conceptual models have limited physical interpretability. In this category, it is worth mentioning the Agriculture NonPoint Source (AGNPS) model (Young et al., 1989). The major drawbacks of conceptual models are that calibration is site-specific and that soil mechanical properties and rainfall characteristics are only taken into account indirectly. (Cuomo et al., 2015)

II.3.1. Physically based models.

It is difficult to describe the rate of soil erosion in the watershed over spatial and time scales due to limitations in the field measurements for each part of the watershed. In order to ensure that measurements are not biased by a few years of abnormally high rainfall or an extreme event, long-term measurements are required to build a sufficient database. Long-term measurements are also needed in order to investigate the response of erosion rates to alterations in climate and land use or the efficiency of erosion control measures. To counter these difficulties, computer based physical models can be used for erosion prediction over a wide range of conditions. (Pandey et al., 2016)

Physically based soil erosion and sediment yield models came into existence after the 1970s, when mainframe computers became readily available, and since then, a variety of such models have been developed ranging from very simple to very complex, and new developments are still in progress (Pandey et al., 2016). Physically based approaches describe the features and mutual interactions of all the main rainfall-induced processes in a catchment, such as infiltration, runoff, rain splash erosion, flow detachment and the transportation/ deposition/remobilization of sediments.

These models require many more input data and parameters for simulation efforts, and are generally over-parameterized. Use of larger number of parameters benefit to yield a better fit of observed data and increase in degree of freedom. Although, it is not necessary that models with larger number of parameters always achieve better results than models with limited number of parameters (Perrin et al., 2001 cited in Pandey et al., 2016)

When time and money are constraints, it is not possible to estimate soil erosion and sediment yield by considering the entire catchment area/watershed at the same time for implementing erosion control measures. In such a situation, physically based modelling not only helps to identify priority areas on the basis of sediment yield but also helps to evaluate the best management practices (BMPs) for the priority sub-watersheds in a short time and with minimum investments. (Pandey et al., 2016)

The main contributions of physically-based models to understand and simulate soil erosion processes in comparison with empirical/conceptual approaches are, (i) more accurate extrapolation to different land use; ii) more correct representation of erosion/deposition processes; (iii) application to more complex conditions including spatially varying soil properties and surface characteristics; (iv) more accurate estimation of erosion/deposition and sediment yield on a single storm event basis (Lane et al., 2001).

Input data used to support the physically-based model and its parameters are major factors affecting the quality of model predictions. Besides, the major issues facing the practical application of physically based models are the requirement of extensive input data, natural complexity, model complexity, and accuracy.(Pandey et al., 2016)

An exhaustive review of worldwide applications of the reviewed models revealed SWAT, WEPP, AGNPS, ANSWERS and SHETRAN models to be the most promising ones for simulation of erosion and sediment transport processes, and therefore, these can be better used for implementation of best management practices (BMP).(Pandey et al., 2016)

II.4. Applications of WEPP model.

WEPP has been applied to several regions around the world for runoff and sediment yield predictions from agricultural and forested areas (De Mello et al., 2016)

Tiwari et al. (2000) evaluated the prediction of soil loss from natural runoff plots at 20 different locations in the United States using the WEPP model and compared the results with measured data and with the predictions made by USLE and RUSLE. They concluded that the model performance is close to the traditional empirical methods without calibration of any parameter. This is one of the strengths of a process-based erosion model of this type in that calibration may not be needed for application of WEPP depending on the users objectives or immediate needs. For example, a field conservationist interested in making erosion model assessments may only wish to compare relative results from different farming management activities and likely would not conduct any model calibration. On the other hand, a graduate student with a set of erosion experiment data might apply the model in an uncalibrated mode initially but then decide to examine how the simulation results might be improved through a calibration/validation exercise (Flanagan et al., 2012).

In the literature, some researchers have successfully applied WEPP with no calibration in their studies. Maalim et al. (2013) using the Geo spatial interface for WEPP in uncalibrated mode, compared sediment yields and runoff fluxes and assessed erosion susceptibility under multiple land use/land cover scenarios in the Le Sueur River watershed, Minnesota (USA). According to the authors, the model gave a realistic picture of the rate of upland soil erosion.

However, it is also common practice to first calibrate a physically based model such as WEPP with field data and then ensure model validity in comparing simulation results with field measurements and finally use the validated model for prediction of soil loss and sediment yield in other areas of similar conditions (Pandey et al., 2016).

Most of the GeoWEPP model applications found in the literature followed the same procedure even if they were limited with the availability of long-term experimental dataset from erosion plots in each part of the watershed. Alternatively, an empirical WEPP calibration was conducted based on yet rarely available long-term measurement of Total suspended solid (TSS) implicitly assuming that all sediments are derived from terrestrial erosion (Maalim et al., 2013). In Reza Meghdadi (2013), runoff and sediment data measured at the outlet of the watershed during one year (2000) were used to successfully calibrate the model where a close correlation between the values of observed and simulated Sediment yield was demonstrated for the calibration period based on the performance evaluation indicators calculated NSE=0.82 and RMSE=0.01549. The calibrated GeoWEPP model was then used to predict sediment yield, identify the most susceptible sub watersheds to erosion and evaluate the impact of effective management practices on daily sediment yield.

In Özalp et al. (2017), The performance and the accuracy of GeoWEPP was assessed by using the observed annual average sediment amounts measured (between 1988 and 2001) from a proximate watershed sharing many similarities in terms of topography, vegetation cover, and land use types with the studied watershed (Godrahav Creek Watershed (GCW) located in northeastern Turkey) where measured data were lacking. In the appointed study, the observed values from the model watershed were then compared to those predicted by the GeoWEPP model for the same years in the studied watershed. The unacceptable large differences between the observed and predicted values were reduced thanks to a calibration game that consists in a trial and error approach of increasing/decreasing by certain percentage the initial values of the key parameters namely effective hydraulic conductivity (Ke), rill erodibility (Kr), interrill erodibility (Ki), and critical shear stress (τcr) until a best fit for GeoWEPP prediction of annual sediment yield is reached. In this case, the goodness-of-fit criterion known as Nash–Sutcliffe coefficient was found equal to 0.877 which correspond to a good model performance. The calibrated model was then used to identify the most susceptible watersheds to erosion.

The GeoWEPP model predict the sediment yield using one intrinsic simulation method called the watershed simulation method or offsite method which use one soil and one management (the dominant ones) for each hillslope losing the spatial variability of the study area for these parameters. The values reported represent the amount of sediment that leave each hillslope and being reported at the outlet. Unlike the watershed method, the values reported in the Flowpath method (second method of simulation) refer to the amount of erosion or deposition occurring in each raster cell of the catchment. This method retains the diversity and spatial distribution of the soil and land use layers which makes it more reliable in terms of soil loss estimation (Minkowski, 2008).

Therefore, a thorough soil loss distribution analysis based on the flowpath simulation output would have been enriching to the above cited studies and many more in the literature that focused only on the offsite simulation method in their search of insights into erosion and sedimentation dynamics at the watershed scale for an informed and effective soil conservation planning. This would have helped in addressing the knowledge gap regarding the accurate prediction of local changes in a watershed affect sediment loads measured at the outlet of a large watershed (Smith et al., 2011 cited in Maalim et al., 2013).

The WEPP model was also compared to other physically based watershed hydrology-erosion models. In Shen et al. (2009), the WEPP model and the Soil and Water Assessment Tool (SWAT) model were applied to simulate runoff and sediment yield for the Zhangjiachong Watershed in the Three Gorges Reservoir Area in China. The simulated runoff and sediment yield values were compared with the measured runoff and sediment yield values. Based on goodness-of-fit criteria the WEPP values were more acceptable than those of SWAT both in the calibration and validation period. The study reported that overall WEPP simulations were better than SWAT in most cases, and could be used with a reasonable confidence for soil loss quantification in the Zhangjiachong Watershed.

No literature was found on the application the GeoWEPP model in our study area or in any other watershed in Morocco. This study will be the first attempt at using the GeoWEPP model to assess the soil erosion in Wadi El Malleh watershed and as powerful guide in soil conservation planning.

CHAPTER III: MATERIALS AND METHOD

III.1 Study area description

III.1.1 Location of the study area.

Wadi El Malleh watershed is located in the northern part of Fez in the boundary between Saiss plain and the southern Rif wrinkles (Tghat and Zalagh); it is surrounded by Wadi Mekkes watershed from the North and West, to Saiss plain from the South and Wadi Sebou valley from the East. It extends over an area of 34 Km^2.

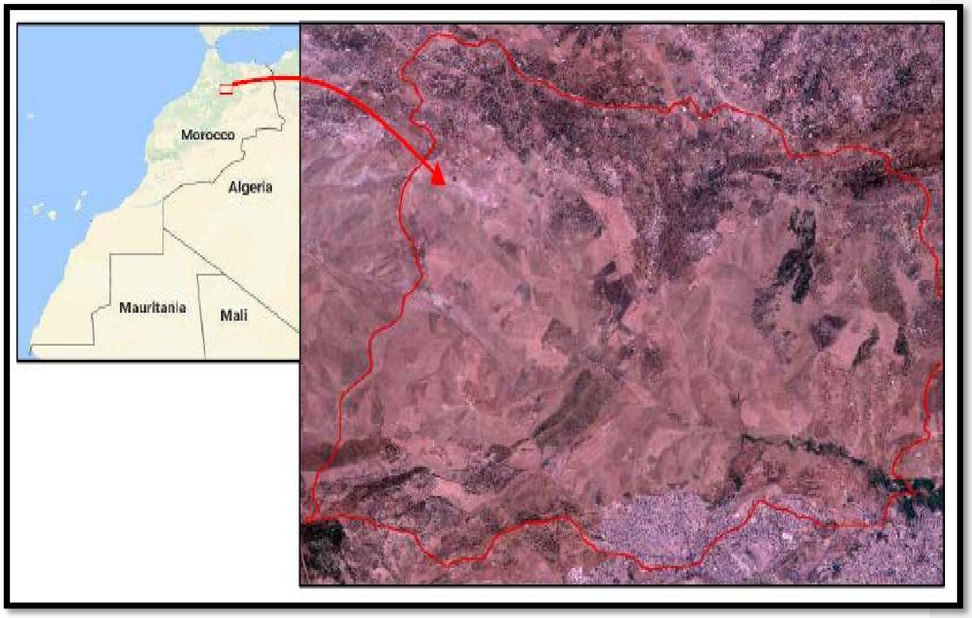

Figure III-1: Geographic location of the study area (El Garouani et al., 2017)

III.1.2. Climate of the Study Area.

III.1.2.1. Precipitations

Precipitations are one of the hydrologic cycle and an important factor of erosion. Therefore, a succinct study of its regime is paramount for the characterization of the climate in the study area. Monthly Rainfall data observed at FES-Saiss weather station for the period 1979 to 2017 were obtained from the Water Resources Division of FES.

The figure III-2 shows the interannual rainfall variability for the period 1979 to 2017 in the study area. The average total annual rainfall is 399.16 mm. The highest value (834.7 mm) was observed for the year 2010 whereas the lowest value of 169.8 mm correspond to the year 2017.

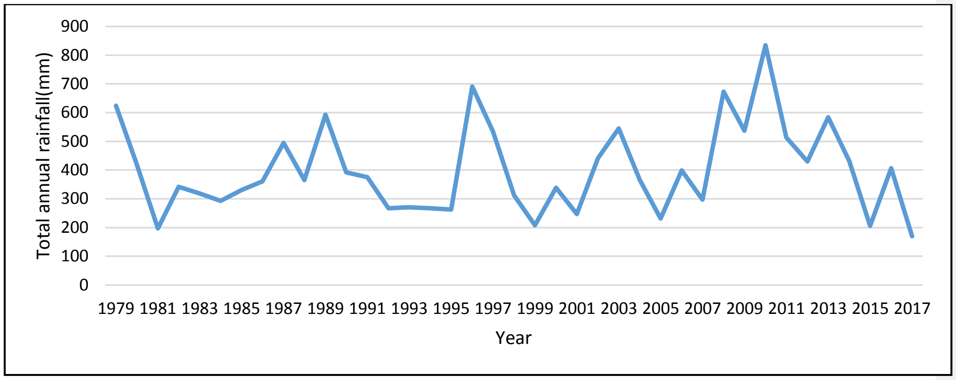

Figure III-2: Interannual rainfall variability for the period 1979 to 2017.

The analysis of the monthly rainfall variability reveals a Mediterranean regime type characterized by alternating wet and dry months. The months corresponding to highest values of rainfall are: November, December, and January to April whereas the dry months corresponds to June, July and August. (See figure III-3)

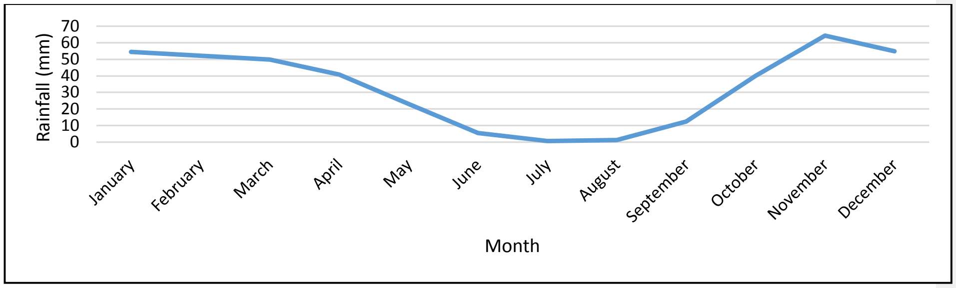

Figure III-3: Average monthly rainfall for the study area (1979-2017)

III.1.2.2. Temperatures

The figure III-4 shows the average monthly mean temperature variability in our study area. The lowest value (9°C) correspond to the month of January whereas the highest value (28.2) correspond to the month of august. The annual average monthly mean temperature is equal to 14.37 °C.

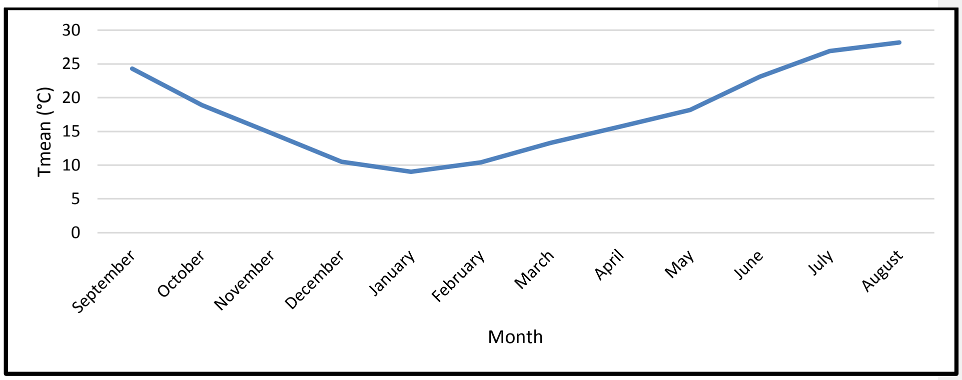

Figure III-4: Average monthly mean temperatures for the period 1978/79- 200/2001 (Source: El Aroussi, 2014)

Based on De Martonne (1942) aridity index I defined as follows:

I = P / (T + 10), Where P is the Average total annual rainfall in mm and T is the Annual average monthly mean temperature in °C. Therefore, for our study area, I=399.16/ (17.77+10) = 14.37 which corresponds to a semi-arid climate according to the following classification.

I<5: Hyper arid climate.

5<I<10: Arid climate.

10<I<20: Semi-arid climate.

I>20: Dry sub humid climate.

III.1.3. Topography.

Based on a 30m-resolution ASTER DEM downloaded from the CGIAR consortium for Spatial Information (CGIAR-CSI) website, the elevation map our study area (figure III-5) were prepared in ArcGIS 10.3. More than 80% of the watershed area is distributed between 300 and 600m elevations (See table III-1). The maximum and minimum elevation values are respectively 897m and 258m.

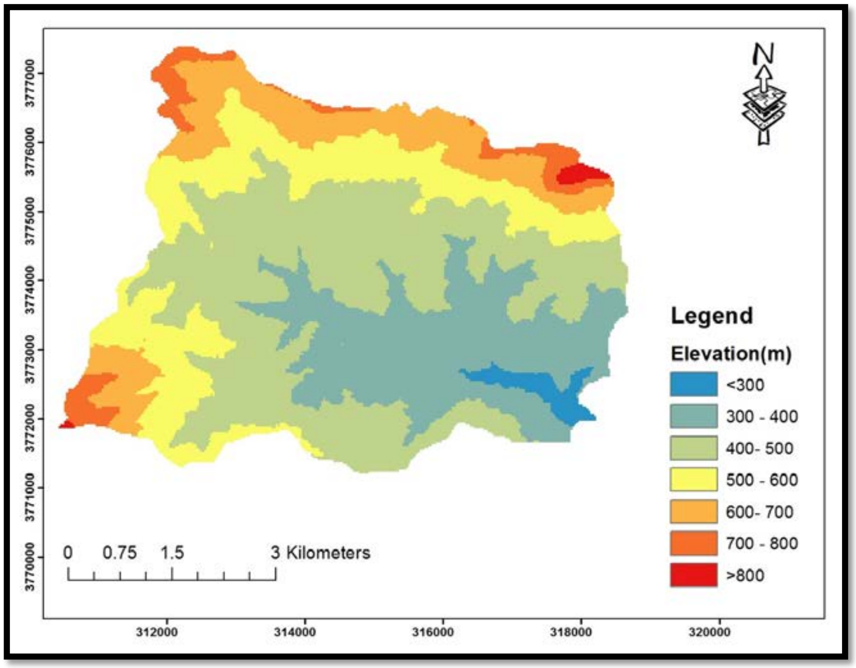

Figure III-5: Elevation map of Wadi El Malleh Watershed

Table III-1: Spatial distribution of altitudes

ID	Elevation class (m)	Area (Km2)	Percentage (%)
1	<300	0.60	1.75
2	300-400	7.77	22.51
3	400-500	13.30	38.54
4	500-600	6.85	19.83
5	600-700	4.40	12.74
6	700-800	1.43	4.15
7	>800	0.17	0.48

The Slope map was also created based on the downloaded DEM and reclassified and ranked in 5 classes based on the established classification in FAO (2001) cited in (Estifanos, 2014) where 1 correspond to lowest runoff potential and 5 to the highest runoff potential (See Table III-2).

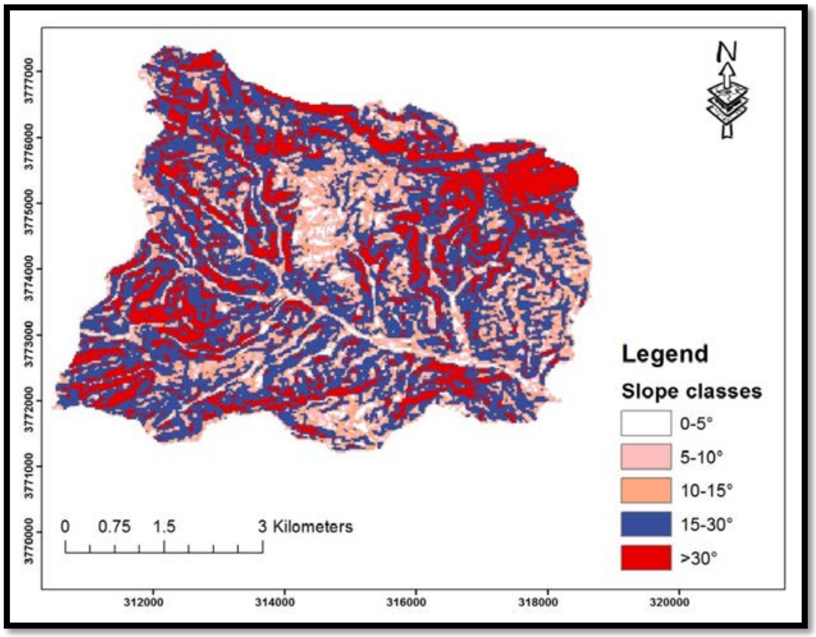

Figure III-6: Slope map of Wadi El Malleh Watershed.

Almost 70% of our studied watershed was found be under high to very high erosion risk based on the slope land (see Figure III-6 and Table III-2)

Table III-2: Slope distribution (in percent of total watershed drainage area)

Rank	Erosion risk	Slope class	Area (km²)	Percentage (%)
1	Very low	0-5°	1.40	4.05
2	Low	5-10°	3.71	10.75
3	Medium	10-15°	5.51	15.96
4	High	15-30°	16.72	48.47
5	Very High	>30°	7.17	20.77

III.1.4. Soil

Twelve soil units are identified in Wadi El Malleh watershed. In the table III-3, they are ranked based on their percentage of occupation. The 5 most dominant soil units are in order the units 15, 4, C2_316, 17 and 3. The figure III-7 show their spatial distribution and location in the studied watershed.

Table III-3: Soil type distribution in Wadi El Malleh (in percent of total watershed drainage area)

Soil unit Id	Soil Class	Area (Km^2)	Percentage (%)	Rank
15	Vertisol	10.12	29.21	1
4	Regosol	7.74	22.35	2
C2_316	Complex unit	6.10	17.61	3
17	Calcisol	4.25	12.27	4
3	Regosol	2.45	7.06	5
10	Regosol	1.09	3.16	6
16	Calcisol	0.76	2.20	7
19	Kastanozem	0.75	2.16	8
C1_234	Complex unit	0.70	2.03	9
1	RockOutcrop/Dolomite	0.31	0.89	10
14	Vertisol	0.24	0.68	11
6	RockOutcrop/Lithosol	0.13	0.39	12

The summarized results of an extensive soil survey (El Aroussi, 2014) and laboratory analysis of the soil samples taken from the different identified soil units are presented in the table III-4.

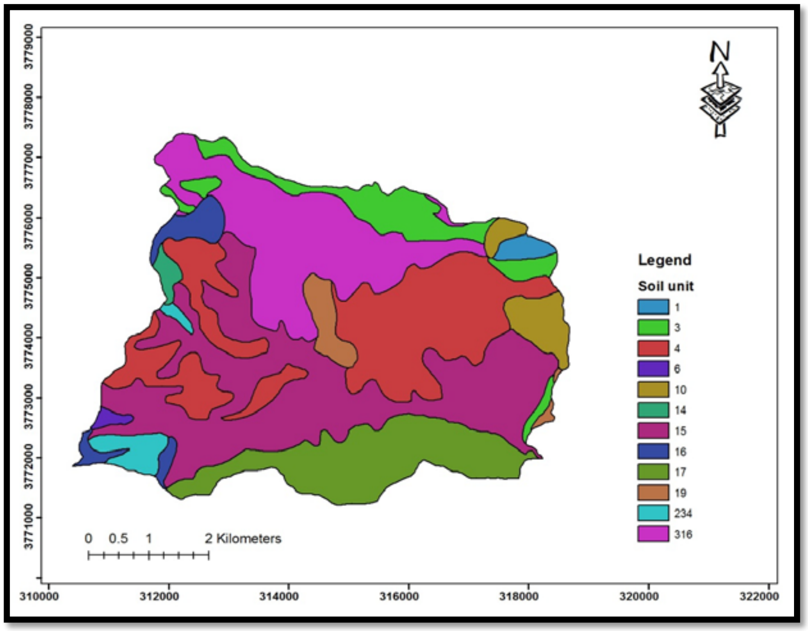

Figure III-7: Soil map (Source: The Laboratory of Geo-Resources and Environment of the Faculty of Sciences and Techniques of Fez)

Table III-4: Measured soil unit characteristics (El Aroussi, 2014)

Soil unit	Clay (%)	Sand (%)	Soil bulk density (g/cm3)	Porosity (%)	Organic matter content (%)
3	19	51.1	0.66	75.09	14.1
4	11	66.3	0.55	79.25	8.7
10	9.2	68.2	0.49	81.51	7.7
15	26.4	22.5	0.59	77.74	6
16	40.7	9.6	0.58	78.11	10
17	27.4	24.3	0.58	78.11	1.4
19	22.2	46.8	0.54	79.62	7.9
C1_234	32.1	3.6	0.58	78.11	5
C2_316	9.1	78.9	0.51	80.75	7

III.1.4. Land use

Wadi El Malleh watershed is highly dominated with agricultural land uses that could divided in perennial (olive) and annual cropping (Cereals) zones or rain fed and irrigated agriculture. Besides the large cropland, other land use land cover (lulc) types namely the raw land, urban, reforested zones, bad land are also observed in less proportion across the studied watershed. The figure III-8 show the spatial distribution of the different land use classes and their specific share (%) in the total watershed area are presented in the table III-5.Following is the description of the method used to map the different land use classes in the study area.

Commenté [A1]: More detail for this section:
-Data used (image and date)
-Used method (photo-interpretation)

Visual interpretation of a Google Earth derived imagery was used for land uses mapping in Wadi El Malleh Watershed. First of all, a vector layer of the study area was geometrically corrected using the Molodensky method in ArcGIS 10.3 from Merchich (degrees) geographic coordinate system to WGS 1984 after which it was converted into KML format. The vector layer in KML format was then imported in Google Earth and the images date set to 26/12/2017. The high spatial resolution of the image and the pre-knowledge (from our supervisor) of the relationship between the different land uses classes, texture and historical information of the study area helped to identify and locate the land use classes more representatively of the real terrain conditions. Polygons corresponding to the different land use classes were meticulously digitized within the studied watershed limits. The KML format of the studied watershed vector layer including the different polygons was visualized in ArcGIS 10.3 and converted into shapefile. Finally, the geographic coordinate system was brought back to Merchich (degrees) from WGS 1984 again using the Molodensky method which led us to the classified map from visual interpretation of Google earth image. The land use map in the figure III-8 was projected into WGS 1984 UTM Zone 30N to meet the GeoWEPP use requirements.

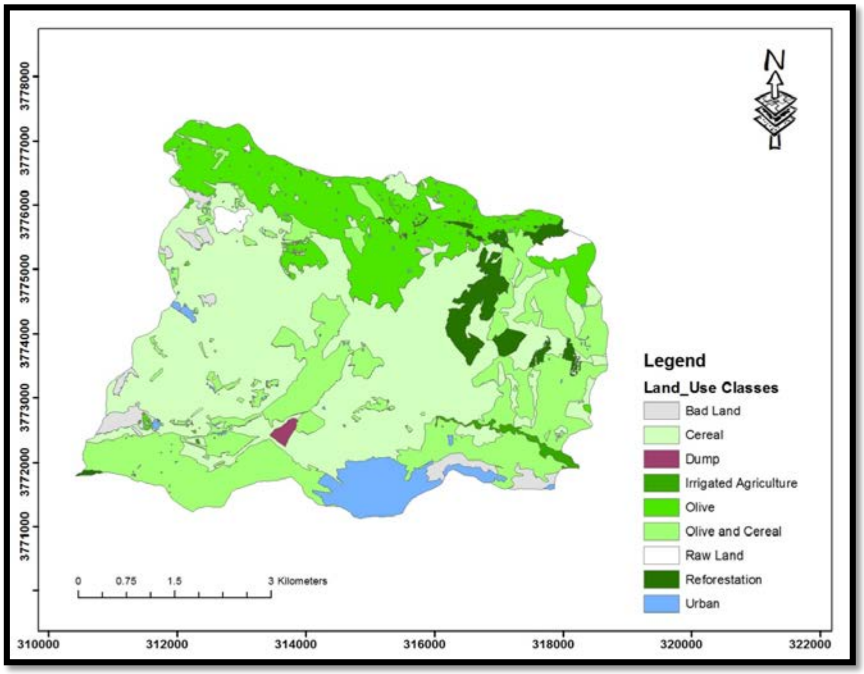

Figure III-8: Land use map

Table III-4: Land use types distribution

Code	Land use class	Area	Percentage (%)
2	Bad land	0.80	2.33
4	Cereal	15.61	45.40
6	Cereal and Olive	8.62	25.08
8	Olive	5.99	17.41
10	Urban	1.42	4.13
12	Irrigated Agriculture	0.20	0.59
14	Raw land	0.46	1.34
16	Dump	0.08	0.25
18	Reforestation	1.19	3.47

III.2. Water Erosion Prediction Project (WEPP) model description

The WEPP watershed model is a continuous simulation computer program that predicts sediment yield and deposition from overland flow on hill slopes, sediment yield and deposition from concentrated flow in small channels, and sediment deposition in impoundments. It computes spatial and temporal distributions of sediment yield and deposition, and provides explicit estimates of when and where in a watershed or on a hill slope that erosion occurs so that conservation measures can be selected to most effectively control soil erosion. (Flanagan & Nearing, 1995)

III.2.1. Spatial representation

In the WEPP watershed model, a watershed is divided into one or more overland flow elements (OFEs), which are areas of uniform soil properties, slope and management. The watershed consists of hill slopes, channels and impoundments; the smallest possible watershed being one hill slope and one channel. Each hill slope is represented as a rectangle.

Runoff, detachment and deposition are first calculated on each hill slope, with the hill slope component of WEPP for the entire simulation period. Then the model combines simulation results from each hillslope and performs runoff and sediment routing through the channels and impoundments. It is intended for use on small agricultural watersheds in which the sediment yield at the outlet is significantly influenced by hill slope and channel processes, and has a recommended maximum size field of 2.6 km^2 (Foster et al., 1987). Despite this limitation, WEPP capabilities have been tested on watersheds larger than 2.6 km^2 (Amore et al., 2004; Baigorria and Romero, 2007; Pandey et al., 2008 cited in Shen et al., 2009).

III.2.2. Surface runoff

Runoff is estimated by the WEPP model as it is an important factor contributing to soil erosion. The hydrology component is based on the water balance equation, which accounts for processes such as precipitation, evapotranspiration, surface runoff, and return flow and soil water storage (Shen et al., 2009).

Runoff is computed using kinematic wave equations and an approximation to the kinematic wave solutions. Infiltration is computed using an implementation of the Green– Ampt Mein Larson (GAML) model for unsteady intermittent rainfall:

$$f_{inf,t} = K_e \left(1 + \frac{\psi_{wf}\Delta\theta_v}{F_{inf,t}}\right) \quad \text{(Eq. III-1)}$$

Where $f_{inf,t}$ is the infiltration rate at time t (mm/h), K_e is the effective hydraulic conductivity (mm/h), ψ_{wf} is the wetting front matric potential (mm), $\Delta\theta_v$ is the change in volumetric moisture content across the wetting front and $F_{inf,t}$ is the cumulative infiltration at time t (mm).

The peak discharge rate at the channel (sub-watershed) or watershed outlet is computed by two methods, depending on whether the model is run in continuous or single-storm mode and if there are multiple OFEs. They are: (1) the equation used in the chemicals, runoff, and erosion from agricultural management systems (CREAMS); and (2) a modified version of a rational equation similar to that used in the EPIC model.(Shen et al., 2009)

III.2.3. Soil erosion

In the WEPP model, watershed sediment yield is calculated from both hill slope and channel areas as a result of detachment, transport and deposition of sediment. The movement of suspended sediment on rill, inter-rill and channel flow areas is based on a steady-state erosion model that solves a sediment continuity equation at peak runoff rate. The steady-state sediment continuity equation is described as:

$$\frac{dG}{dx} = D_f + D_i \qquad \text{(Eq. III-2)}$$

Where G is sediment load (kg $s^{-1}m^{-1}$), x represents distance downslope (m), D_f is rill erosion rate (kg s^{-1} m^{-2}) and D_i is inter-rill sediment delivery to the rill (kg s^{-1} m^{-2}). D_i is considered as independent of x, and always >0. D_f is >0 for detachment and <0 for deposition.

For model calculations, both D_f and D_i are computed on a per rill area basis, thus G is solved on a per unit rill width basis. After computations, sediment yield is expressed as sediment yield per unit land area. Besides rill and interrill erosion processes, residue and canopy effects on soil detachment and infiltration, surface sealing, plant growth, climate and tillage effects on soil properties, effects of soil random roughness and contour effects, including the potential overtopping of contour ridges among others are computed in the WEPP model. A detailed description of each model component can be found in the USDA Water Erosion Prediction Project hillslope and watershed model documentation.(Flanagan & Nearing, 1995)

III.3. GeoWEPP setup

The GeoWEPP model used in this study is the link between two independent software products; WEPP Model Version 2012 and ArcGIS 10.3 (ESRI, Redlands, CA). The GeoWEPP package for ArcGIS 10.3 includes two tools that further expand its utility, the Topographic Parameterization tool (TOPAZ) and Topwepp software products developed by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS). The TOPAZ tool generates hillslope profiles by parameterizing topographic data using a given digital elevation model (DEM). It processes the 30-m DEM based on the D8 method, the slope-of-steepest descent routing concept, and the critical source area (CSA) concept (Garbrecht and Martz, 1997 cited in Maalim et al., 2013). These analyses provide the needed input data for subsequent delineation of a watershed, sub-catchments, flow direction grid and channel network extraction.

Hillslopes and their slope profiles are thus explicitly defined and prepared for further characterization by Topwepp. The assignment of land cover and soil types to hillslopes is done by Topwepp, which uses grid-based information stored in the raster layers of land cover and soil type. Thus, each grid cell within a given hillslope will have a specific land cover and soil type assigned to it. The Topwepp program also executes the model runs and produces the output maps (Maalim et al., 2013)

III.4. Data Processing for GeoWEPP Simulation

In order to predict soil erosion using the WEPP model, it is necessary to supply the four relevant group of input files corresponding to climate, land cover, soil, and slope data (Puno, 2014)

III.4.1. Slope input data preparation.

Two 30m-resolution ASTER DEM layers covering our study area were downloaded from the CGIAR consortium for Spatial Information (CGIAR-CSI) website, joined into one and reprojected into WGS84-UTM zone 30 coordinate system in ArcGIS 10.3. The reprojected DEM was clipped to size it to the study area extent. The clipped DEM was converted into ASCII format as input into the GeoWEPP model.

III.4.2. Soil input data preparation.

The Geo WEPP interface makes use of digital soil maps in which the different polygons represent different soil units. The soil files corresponding to the different soils units have to be prepared in the WEPP software or selected from WEPP soil database. The required soil data (sand and clay ratios, organic matter content) were obtained from a study (El Aroussi, 2014) conducted in the same watershed that included a field soil survey and laboratory analysis for the samples taken from the nine main soil units.

Soil map layer was created for the GeoWEPP interface. Initially, a vector polygon map converted into a raster-based data model. The resulting map was converted into ASCII and saved as soilsmap.asc file. The procedure described in (Minkowski, 2008) was followed in creating the soil map layer.

III.4.3. Management input data Preparation

The identification of the different land use patterns in the study area was carried out using the photo interpretation technique of a Google Earth image dated December 26th 2017 where the polygons corresponding to the different land uses were digitized as explained in details in the section III.1.4. Just like for the soil input preparation, the vector polygon land use map was first converted into a raster-based data model before the final conversion into an ASCII file as required in GeoWEPP.

Built-in management databases of WEPP that best suit the field conditions were selected to be associated with the different land use classes identified in our study area following the procedure described in (Minkowski, 2008).

III.4.4. Climate Data Processing

To generate climate file with daily values of precipitation, temperature, solar radiation, and wind speed obtained from the weather stations, the WEPP model uses CLIGEN (Climate Generator), which is a stochastic weather generation model (Yüksel et al., 2008). Since the meteorological database in Morocco is not generated in the data format of the CLIGEN model, the climate parameters for the study area were obtained from FES-SAISS weather stations and subsequently transformed into the format used in CLIGEN. The input climate parameters are the maximum and minimum air temperature and precipitation.

III.5. Model simulation

The GeoWEPP simulation model involve two methods, the offsite (watershed simulation) and the onsite (flowpath simulation). The offsite determines a representative profile for the hillslopes within the catchment and assigns one soil and one land use treating the profile as unique. This method is called the offsite assessment because the values represent the amount of sediment, leaving each hillslope evaluated at the outlet. The offsite method helps the user to identify which hillslopes are the problem areas in the study. The onsite method shows which portions of a particular hillslope are the main contributors of such erosion problem, considering the diversity and distribution of the soil and land use types (Puno, 2014).

Model simulations were executed using both the watershed and flowpath methods. A 30-year simulation run in WEPP using the climate file discussed above generated estimates of annual runoff, soil loss, and sediment yield. The Topwepp component of GeoWEPP mapped the 30-year average soil loss and sediment yield outputs using a Tolerable Soil Loss scheme.

We systematically assessed the onsite and offsite magnitude of erosion first at the watershed level and then sub watershed wise by selecting an outlet for the eventual appointed drainage area. Reports corresponding to the two methods of simulation and summarizing the results concerning the total runoff, soil loss, soil deposition and sediment yield are automatically generated after each simulation.

CHAPTER IV RESULTS AND DISCUSSION

Following the creation of the four categories of input files required by the GeoWEPP model and their introduction into the model, the predicted values for soil loss and sediment yield were calculated using the two simulation options available namely watershed simulation or offsite method and flowpath simulation or onsite method. The channel network structuring was done by setting the CSA (Critical Source Area) at 25ha and MSCL (Minimum source channel length) at 500 m, the main outlet for the whole watershed was optimally selected after several attempts to include the maximum possible area of the Wadi El Malleh watershed (3057.12 ha)

IV.1. Onsite assessment.

The estimated soil loss map of our study area is shown in Fig. IV-1. The results of running the model for 30-year continuous simulation on each pixel of the DEM are expressed in t/ha/yr. The derived soil loss distribution map help to visualize the areas that are most susceptible to erosion. A Tolerable soil loss level of 50 t/ha/yr was used to averagely map the distribution pattern of soil loss rates in the watershed studied. Low soil loss rates less than 12.5 t/ha/yr are mainly found in the northern part of the Wadi El Malleh watershed whereas the southern part in general and the south-western part mostly are severely affected and correspond to extremely high soil loss rates above the threshold of 35 t/ha/yr in the region according to Sadiki et al. (2009).

Thanks to zonal histogram tool in ArcGIS10.3 software, the onsite soil loss distribution map for the whole watershed was used to derive the frequency distribution of its cell values (of soil loss) on the value input of the different zone types of land use, soil and slope classes as shown in the following sections.

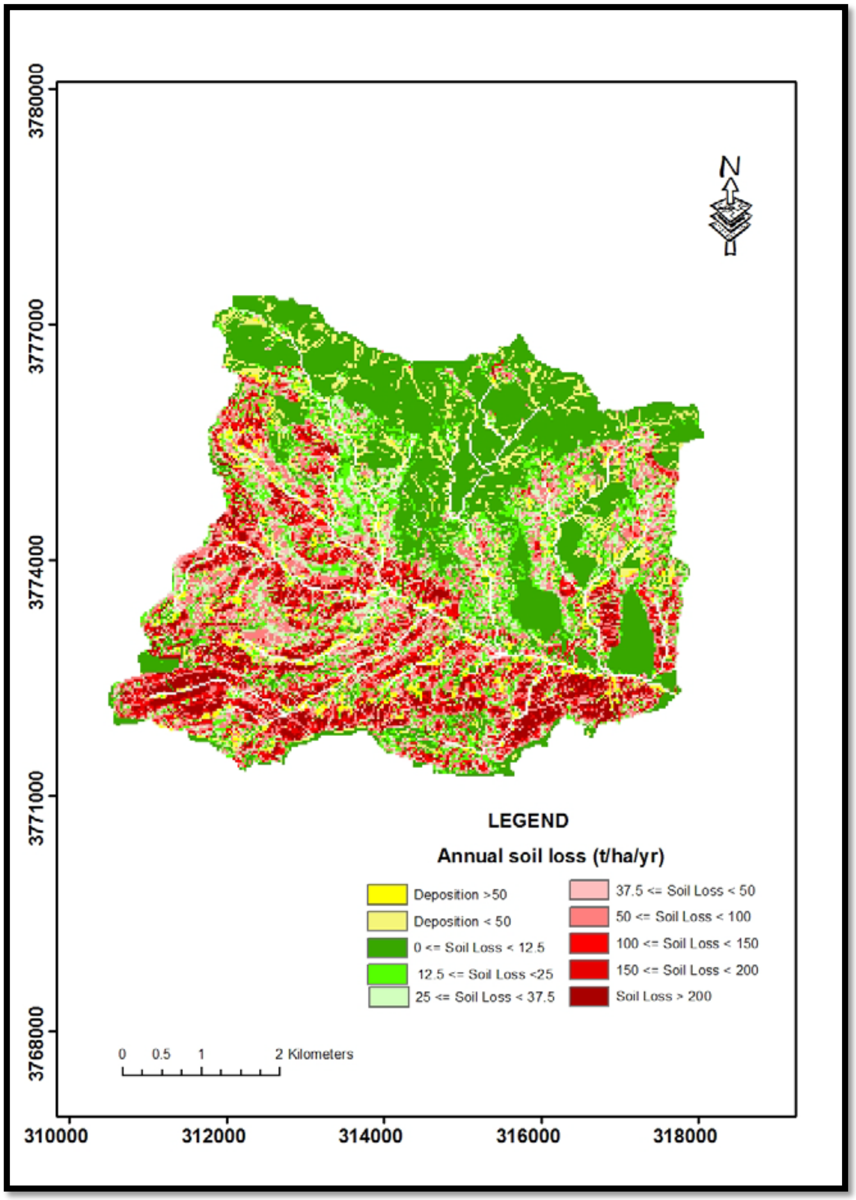

Figure IV-1: The Distribution of annual soil loss amount within Wadi El Malleh watershed

IV.1.1. Distribution of soil loss rates across soil types and land use types.

In terms of pedology, the watershed studied is dominated by four different soil units: unit 4(24.14%), unit 15(28.28%), unit 17(12%) and the second complex unit C2_316 (19.29%). The soil loss distribution across the different soil types is shown in the table IV-1. Considering the area under each soil type concerned with soil loss rates above 37.5 t/ha/yr; the unit 17 is the most susceptible dominant soil type in the watershed with 65.21% of its area affected with extremely high erosion rates (>35 t/ha/yr), followed by the unit 15 (62.34%) whereas only the unit 4 and far more the unit C2_316 are less susceptible to soil erosion with respectively 33.73% and 7.11% of their area with soil loss rates above 37.5 t/ha/yr.

Table IV-1 Frequency distribution (in %) of soil loss rates across soil types.

Ann. Soil loss(t/ha/yr)	Soil units										
	1	3	4	6	10	14	15	16	17	19	C1_234	C2_316
Deposition > 50	0.54	0.37	3.79	0.00	0.28	1.78	4.27	3.32	3.76	0.74	3.50	1.08
Deposition < 50	12.43	12.22	7.84	0.82	15.10	0.44	2.81	5.67	2.35	4.59	3.38	12.86
0 <= Soil Loss < 12.5	86.49	75.11	24.17	85.25	54.42	17.33	13.26	20.82	11.82	53.23	2.50	60.65
12.5 <= Soil Loss < 25	0.00	2.89	16.27	0.82	8.26	13.78	8.43	13.59	8.79	13.28	2.50	11.13
25 <= Soil Loss < 37.5	0.00	1.79	14.19	0.00	7.69	10.22	8.89	10.36	8.08	8.56	3.75	7.18
37.5 <= Soil Loss < 50	0.00	1.83	11.58	2.46	6.55	7.56	8.29	8.02	7.40	5.09	5.00	3.44
50 <= Soil Loss < 100	0.00	3.54	17.34	8.20	4.56	20.89	20.44	17.79	18.90	10.42	21.25	2.85
100 <= Soil Loss < 150	0.00	1.30	2.81	0.00	0.57	16.89	13.03	12.02	11.11	2.36	16.25	0.51
150 <= Soil Loss < 200	0.00	0.45	0.86	0.00	0.85	4.44	8.62	5.08	8.56	1.12	10.50	0.24
Soil Loss > 200	0.54	0.49	1.14	2.46	1.71	6.67	11.96	3.32	19.24	0.62	31.38	0.07

Despite being covered at 84.16 % with “Cereal” and “Cereal and Olive” the two land use types associated with Winter Wheat conventional till in the WEPP model and having 78.17 % of its area distributed between the 4th and 5th; steepest slopes classes at high erosion risk, the soil unit 4 (see Table IV-2 and Table IV-4) tend to be more resistant to soil erosion than the unit 15 and 17.

Table IV-2 Frequency distribution (in %) of land use types across soil types.

Landuse type	Soil units										
	1	3	4	6	10	14	15	16	17	19	c1_234	c2_316
Bad Land	0.00	1.68	1.94	73.49	0.00	5.94	0.98	3.70	8.03	0.00	0.00	0.46
Cereal	0.00	10.29	71.16	25.90	18.74	75.17	62.43	42.22	17.32	56.13	8.87	28.34
Olive and Cereal	1.34	6.29	13.00	0.00	59.14	16.08	31.99	36.57	43.27	39.23	84.48	9.95
Olive	7.26	75.69	3.55	0.60	15.50	1.40	0.26	0.37	0.00	4.09	0.00	58.96
Urban	0.00	0.84	0.05	0.00	0.75	1.40	0.31	0.56	30.53	0.55	6.65	0.39
Irrigated Agriculture	0.00	0.03	0.00	0.00	0.00	0.00	1.71	0.00	0.85	0.00	0.00	0.00
Raw Land	70.97	3.30	0.00	0.00	0.00	0.00	0.09	13.70	0.00	0.00	0.00	0.61
Dump	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00
Reforestation	20.43	1.88	10.31	0.00	5.87	0.00	1.34	2.87	0.00	0.00	0.00	1.29

Though covering only 2 % of the total watershed area, the complex unit C1_234 is the most susceptible soil unit to erosion with 84.38% (see table IV-1) of its total area under extremely high soil loss rates (>37.5t/ha/yr). The main reason being that 90% of its area is distributed on the steepest slopes (see table IV-4) in addition to being covered with Olive and Cereal at 84.48% (table IV-2).

Table IV-3 Frequency distribution (in %) of soil loss rates across landuse types.

Ann. Soil loss(t/ha/yr)	Land use types								
	Bad Land	Cereal	Olive and Cereal	Olive	Urban	Irrigated agriculture	Raw Land	Dump	Reforestation
Deposition > 50	3.69	3.82	3.71	0.35	1.65	3.08	1.91	3.37	2.54
Deposition < 50	3.01	5.04	4.44	13.38	2.80	2.31	17.44	3.37	16.80
0 <= Soil Loss < 12.5	20.52	16.35	17.79	79.44	20.52	75.38	70.03	8.99	68.03
12.5 <= Soil Loss < 25	6.29	14.42	10.33	2.60	13.15	6.92	3.54	8.99	3.31
25 <= Soil Loss < 37.5	5.75	12.44	9.36	1.73	10.29	0.77	2.18	16.85	2.77
37.5 <= Soil Loss < 50	8.76	9.74	8.46	0.89	7.18	3.08	1.09	13.48	2.62
50 <= Soil Loss < 100	15.46	18.57	17.78	1.07	17.73	6.15	2.72	23.60	3.24
100 <= Soil Loss < 150	8.89	7.98	9.54	0.41	10.42	2.31	0.54	11.24	0.46
150 <= Soil Loss < 200	7.39	4.84	6.44	0.08	5.78	0.00	0.00	3.37	0.08
Soil Loss > 200	20.25	6.80	12.16	0.05	10.48	0.00	0.54	6.74	0.15

The three landuse types namely Bad land, urban and Dump were associated with the pavement WEPP management type which was the best match among the WEPP management database, however from the table IV-3 they tend to be unexpectedly more susceptible to soil erosion with respectively 60.74%, 51.59% and 58.43% of their total area affected with extremely high erosion rates (above 37.5t/ha/yr). In WEPP simulation context, a pavement being a free vegetation land will be associated with high soil erosion rates if the soil type they are installed on, is more susceptible to erosion. This is our case here as it can be shown in table IV-5 where the bad land has respectively 12.49% and 42.25% of its area respectively installed across soil unit 15 and 17. 93.51% of the urban zones installed across soil unit 17 and finally the small dump area is totally (100%) installed across soil unit 15.

Those results are concurrent with those in Maalim et al. (2013) where simulated values of sediment yield and soil loss from urban areas were also surprisingly high which according to the authors is due to the fact that those values are based on runoff estimates and are not accurate pointing out the limitation of WEPP on urban areas.

Table IV-4 Frequency distribution (in %) of slope classes across soil types.

Slope classes	Soil units											
	1	3	4	6	10	14	15	16	17	19	c1_234	c2_316
1st(0-5°)	0.00	2.45	2.19	0.00	2.48	13.24	4.87	2.36	5.83	21.94	1.05	3.72
2nd(5-10°)	0.27	6.71	7.16	4.79	11.89	36.24	12.48	7.55	12.19	33.96	1.86	11.67
3rd(10-15°)	0.54	10.90	12.47	7.78	24.60	21.25	19.57	17.00	17.26	23.37	6.75	19.52
4th(15-30°)	8.06	38.18	47.96	34.13	46.05	28.22	53.20	58.82	45.97	19.07	46.33	45.77
5th(>30°)	91.13	41.76	30.22	53.29	14.97	1.05	9.88	14.27	18.75	1.65	44.00	19.33

The land use types with a vegetal cover and where the soil is less (Irrigated pea crop) or (un-)disturbed (Olive, Raw land and reforestation) proved to be less susceptible to erosion as it is shown in the table IV-3 where we read that only 11.54% for Irrigated agriculture area, 6.55% of reforestation zones, 4.90% of raw land surface and 2.5% of the total area under solely Olive plantations are affected with extremely high erosion rates (37.5 t/ha/yr). Those values are too small compared to Cereal or Cereal/Olive associations where around 50% of their total area experience too high soil erosion rates.

Table IV-5 Frequency distribution (in %) of soil types across land use types.

Soil units	Land use types								
	Bad Land	Cereal	Olive and Cereal	Olive	Urban	Irrigated Agriculture	Raw Land	Dump	Reforestation
1	0.00	0.00	0.08	0.33	0.00	0.00	45.50	0.00	5.71
3	4.79	1.56	1.81	30.87	0.48	0.42	19.05	0.00	2.86
4	18.63	35.10	11.57	4.58	0.12	0.00	0.00	0.00	67.39
6	12.49	0.20	0.00	0.01	0.00	0.00	0.00	0.00	0.00
10	0.00	1.32	7.49	2.99	0.30	0.00	0.00	0.00	4.88
14	2.08	1.09	0.43	0.05	0.00	0.00	0.00	0.00	0.00
15	12.49	39.44	36.14	0.42	1.44	84.58	2.12	100.00	10.80
16	4.16	2.41	3.65	0.07	0.24	0.00	25.22	0.00	2.02
17	42.25	4.86	21.49	0.00	93.51	15.00	0.00	0.00	0.00
19	0.00	2.68	3.47	0.42	0.06	0.00	0.00	0.00	0.00
234	0.00	0.40	6.94	0.00	3.25	0.00	0.00	0.00	0.00
316	3.12	10.93	6.92	60.25	0.60	0.00	8.11	0.00	6.34

IV.1.2. Distribution of soil loss rates across sub watersheds

In the previous section we established the distribution of soil loss rates across the different soil types and land use types; it was important to know which soil unit and landuse type are more susceptible to soil erosion than others. In this section we are going to show how variably soil loss is happening across the different sub watersheds of our study area in other to be able to identify which one is experiencing extremely high soil erosion rates, why it is so and to be able to guide soil conservation planning in those sub watersheds severely affected and exposed than others.

Based on the outlet selected, soil erosion was simulated in each pixel of the area drained through that outlet and a soil loss map was generated (fig. IV-1). To study the distribution of soil loss across the sub watersheds, a catchment with the same dimensions was delineated and subdivided with the help of Arc SWAT extension in ArcGIS 10.3 after which some sub watersheds were merged to get the same subdivision as the one obtained in GeoWEPP after setting CSA at 25ha and MCSL at 500m for channel network delineation. The figure IV-2 show the output of those operations.

Again the Zonal histogram tool under spatial analyst tools in ArcGIS 10.3 was used to generate the frequency distribution of soil loss rates across the different sub watersheds but only the sub watersheds corresponding to the main tributaries obtained according to the channel network in GeoWEPP are analyzed here, which make 10 relatively important sub watersheds. (See figure IV-2 and table IV-5).

Table IV-5 Frequency distribution (in %) of soil loss across sub watersheds.

Ann. Soil loss(t/ha/yr)	Sub watersheds									
	2	3	4	5	6	7	8	9	10	11
Deposition > 50	3.21	2.74	0.58	2.49	3.62	5.82	3.70	6.88	4.51	2.18
Deposition < 50	5.13	9.33	11.75	10.09	3.25	5.50	2.96	2.75	1.84	2.18
0 <= Soil Loss < 12.5	16.05	36.32	67.03	38.03	7.59	5.82	9.43	5.59	6.01	20.14
12.5 <= Soil Loss < 25	12.20	13.73	8.46	12.20	9.84	10.09	7.22	8.10	10.85	12.08
25 <= Soil Loss < 37.5	12.32	10.32	4.59	10.34	11.73	12.48	7.94	9.07	8.18	10.10
37.5 <= Soil Loss < 50	8.99	8.51	2.88	6.56	11.52	11.77	8.07	8.26	7.85	7.41
50 <= Soil Loss < 100	20.54	12.48	3.91	9.94	25.39	21.80	20.67	22.35	20.87	16.84
100 <= Soil Loss < 150	11.42	3.38	0.60	5.14	10.38	7.83	13.64	12.31	14.02	10.10
150 <= Soil Loss < 200	6.80	1.45	0.09	2.86	6.17	5.95	8.84	10.53	9.85	5.48
Soil Loss > 200	3.34	1.73	0.11	2.34	10.51	12.94	17.55	14.17	16.03	13.50

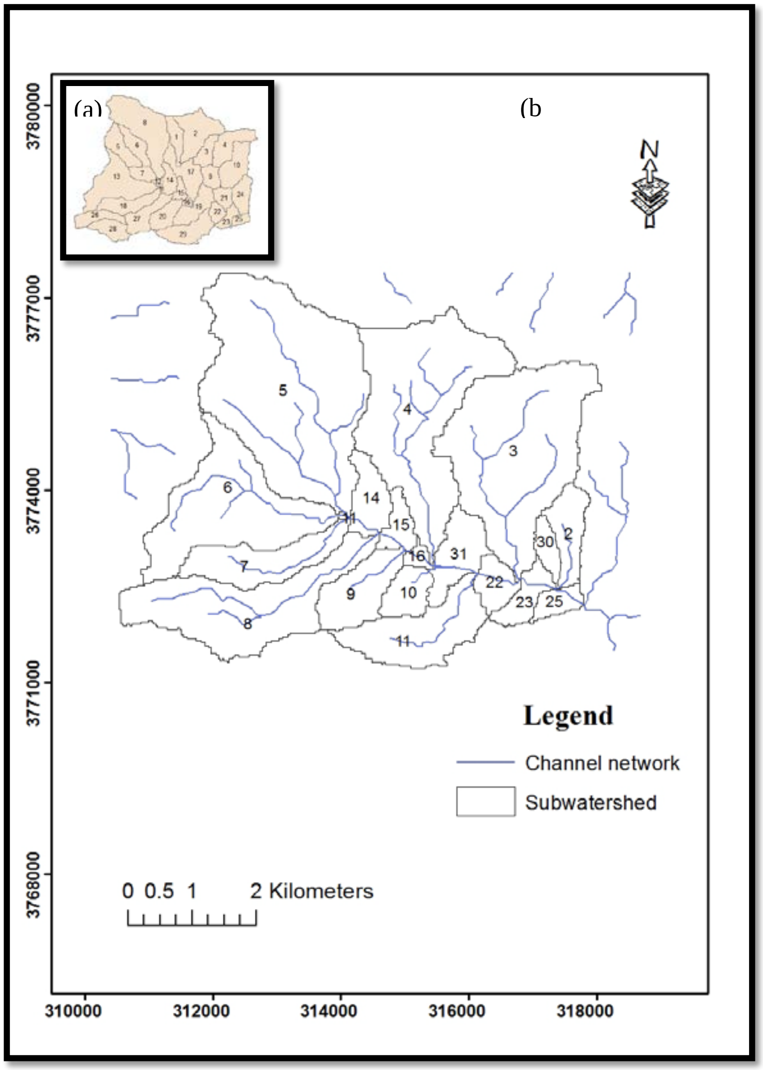

Figure IV-2: Watershed subdivision: (a) Output of Arc SWAT extension (b) After merging some sub watersheds to match the channel network obtained in GeoWEPP.

Considering the percentage of the area under extremely high soil loss rate (>35 t/ha/yr), the ten sub watersheds can be ranked from the most to the least affected sub watershed as follow:

8(68.76%),**10**(68.61%),**9**(67.61%),**6**(63.97%),**7**(60.28%),**11**(53.32%),**2**(51.09%),**3**(27.56%),**5**(26.84%),**4**(7.58%).

The 5 most affected sub watersheds have two things in common: (i) 90% of their area is covered with Cereal or association of Olive and Cereal (table IV-6), (ii) more than 50% of their area is characterized by the most susceptible soil unit to erosion namely the unit 15, 17 and C1_234 as it can be seen in the table IV-7.

Table IV-6 Frequency distribution (in %) of land use types across sub watersheds.

Land use types	Sub watersheds									
	2	3	4	5	6	7	8	9	10	11
Bad Land	0.00	0.05	0.39	2.40	6.46	0.50	0.39	0.00	0.00	6.05
Cereal	38.56	45.51	36.68	51.37	87.63	66.92	21.40	81.14	89.69	4.35
Olive and Cereal	53.24	17.64	5.38	7.55	4.16	30.47	74.65	17.84	0.00	23.85
Olive	0.00	13.64	55.81	35.71	0.22	0.93	0.21	0.00	0.00	0.00
Urban	0.00	0.20	0.42	0.32	1.52	1.12	0.46	0.32	10.31	65.70
Irrigated Agriculture	0.24	0.05	0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.05
Raw Land	0.00	2.01	0.70	2.63	0.00	0.00	0.00	0.00	0.00	0.00
Dump	0.00	0.00	0.00	0.00	0.00	0.00	2.49	0.71	0.00	0.00
Reforestation	7.96	20.89	0.63	0.01	0.00	0.06	0.28	0.00	0.00	0.00

The leading sub watershed n°8 for example having 17.55% of its area experiencing over 200 t/ha/yr has in addition to 55.94% and 16.12% corresponding respectively to soil unit 15 and 17, a portion of 17.73% corresponding to C1_234; the most susceptible soil unit to erosion which appear to be nonexistent in other sub watersheds (table IV-7). The sub watershed 10 at the top of having 89.69% of its area covered with cereals, has 54.99% and 45.01% of its area corresponding respectively to soil unit 17 and soil unit 15 whereas the sub watershed 6 despite having 87.63% of its area covered with cereal (with conventional tillage) has up to 41% of its area corresponding to soil unit 4 which is less susceptible to erosion compared to unit 17 and 15.

Table IV-7 Frequency distribution (in %) of soil types across sub watersheds.

Soil units	Sub watersheds									
	2	3	4	5	6	7	8	9	10	11
1	0.00	3.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	7.51	24.11	8.65	0.00	0.00	0.00	0.00	0.00	0.00
4	2.94	60.46	25.67	11.20	41.17	48.77	0.51	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	2.24	0.00	0.74	0.00	0.00	0.00
10	0.00	5.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	1.24	3.08	0.00	0.00	0.00	0.00	0.00
15	97.06	11.76	1.45	18.04	50.27	51.23	55.94	70.36	45.01	0.00
16	0.00	0.00	0.00	8.07	0.00	0.00	8.96	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	16.12	29.64	54.99	100.00
19	0.00	0.00	7.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
234	0.00	0.00	0.00	0.00	3.23	0.00	17.73	0.00	0.00	0.00
316	0.00	11.38	41.24	52.79	0.00	0.00	0.00	0.00	0.00	0.00

IV.2. Offsite assessment.

In the previous sections, an analysis of soil loss distribution in the watershed was conducted and the most affected zones in the watershed were highlighted and the contributing factors established. The GeoWEPP model provides the opportunity to compute the soil lost from channels which is not negligible and also how much lost soil reach the outlet and is subsequently transported out of the sub watershed boundaries which obviously have adverse effects on water resources offsite.

An outlet for each of the 11 sub watersheds was then selected and the model was ran to simulate erosion and sediment delivery in each sub watershed using respectively the flowpath and watershed methods. The table IV-8 summarizes well the estimation output of runoff, soil loss and sediment yield in each sub watershed helping us to gain more insights into both onsite and offsite impact of erosion in the watershed to guide an effective soil conservation planning.

Table IV-8 Offsite erosion and sediment delivery values on average annual basis

(Sub) watershed	Runoff (mm)	Soil lost from hillslopes(t/yr)	Soil lost from channels(t/yr)	Sediment delivery ratio	Avg. Ann. Sediment discharge from outlet (t/yr)	Area (ha)	Avg. Ann sediment yield (t/ha/yr)
1	40.660	13775.000	2726.100	0.409	6745.300	242.660	27.800
2	57.700	4548.600	245.800	0.458	2194.800	62.140	35.300
3	34.620	24398.700	2764.400	0.377	10239.600	480.400	21.300
4	11.750	2409.600	153.800	0.391	1002.200	453.320	2.200
5	23.520	24688.100	9897.900	0.464	16041.800	657.190	24.400
6	49.800	32716.900	4385.600	0.279	10354.300	316.660	32.700
7	55.740	12950.400	160.900	0.436	5715.400	127.080	45.000
8	59.540	39177.200	2028.200	0.309	12742.900	310.140	41.100
9	60.960	15289.700	5.900	0.471	7203.500	100.580	71.600
10	56.530	7460.500	4.100	0.466	3479.100	47.350	73.500
11	161.200	30358.900	152.200	0.517	15772.800	159.500	98.900

Based on the results presented in the table IV-8, the sub watershed 11 is leading in terms of sediment delivery per unit area of watershed with 98.90 t/ha/yr whereas the lowest value of 2.2 t/ha/yr is the sediment yield from the sub watershed n°4. The same ranking is observed when considered the runoff values.

On the one hand, the sub watershed 11 has a poor vegetal cover with 65% (see table IV-6) of its total area corresponding to urban land use type which was associated to a WEPP management type called pavement in the current study. As it was explained above, this kind of land use is less concerned with erosion because the soil is not exposed to the high runoff (161.2mm) due to the low infiltration rate of pavement surface. Therefore, the soil loss rates extremely low in this watershed to reflect the reality on the ground. On the other hand, the sub watersheds 4 and 5 have the lowest values of runoff because: (i) their soil type is mostly dominated with the complex unit C2_316 which is highly permeable, (ii) they have respectively 55.81% and 35.71% of their total area covered with olive tree which imply less soil disturbance and increased soil resistivity to erosion. The sub watershed 6 has the lowest sediment delivery ratio (SDR) mostly because of a less dense channel network thus low drainage density. The 10th and 2nd sub watersheds have a relatively high sediment yield, respectively 73.5 t/ha/yr and 35.3 t/ha/yr because their relatively small area. This is contrasted with the low sediment yield values for the largest watersheds 3 and 5 despite relatively high values of average annual sediment discharge from outlet (10239.60 t/yr and 16041.800 t/yr respectively).

Considering the source of sediment reaching the outlet, it is clear that for the majority of sub watersheds, the great contribution is that from hillslopes largely exceeding the channel soil loss.

IV.3. Effective management of critical sub watersheds

From the results presented in the tables IV-5 and IV-8 and their analysis conducted in the previous sections, four sub watersheds are severely affected with hillslope erosion with the large portion of the soil lost leaving the sub watershed as sediment yield. The four identified most critical sub watersheds are the: 6,7,8,9.

The sub watersheds 2 and 10 despite having more than 50% of their area under extremely high soil loss and high sediment yield values were not selected before the larger ones with the same characteristics. Again, urban zones occupy more than 10% of 10^{th} sub watershed which is not well represented in the GeoWEPP model. This has obviously led to relative overestimation more aggravated in the sub watershed 11 where urban zones occupy 65.70% (see table IV-6). For these reasons, the sub watersheds 6, 7, 8 and 9 remain the most critical sub watersheds prioritized for effective management planning.

Effective conservation practices should be applied on the whole watershed to improve or preserve the productivity of the limited landed resources but also to limit the negative impact of soil erosion off-site. In this study, one management scenario is applied to the only four most critical watersheds to assess the reduction level of soil loss due to an effective management. As it was shown in the sections above areas under winter wheat, conventional till namely the land uses types “Cereals and Olive/Cereals” were associated with enormous soil loss amount. One effective management strategy would be then to change the land use, reducing the fraction of area occupied with cereals by replacing it with alfalfa crop known for its great qualities in soil erosion control.

GeoWEPP provides the opportunity to change the hillslope soil or land use type and rerunning the model to observe the induced change in terms of soil loss or sediment yield. The hillslopes characterized with Cereal or Olive/Cereal planted on unit 15 soil type, had their land use changed from Cereal or Olive/Cereal to Alfalfa with cuttings.

Villax (1963) has demonstrated the suitability of Moroccan conditions to the extension of the alfalfa crop highlighted the multiple benefits that could be gained from its adoption. In particular, the alfalfa crop is known as one of the most yielding among fodder crop on the top of significantly reducing the soil loss rates due to its expanded soil coverage and its deep, pivoting and developed root system and enriching considerably the soil quality by increasing nitrogen and organic matter content, thus restoring the agricultural productivity.

The table IV-9 show the fraction of cereal converted to alfalfa for each sub watershed whereas on the figures IV-3 to IV-6 the hillslopes changed can be identified. It is important to keep in mind that those maps are the output of the watershed simulation that consider the dominant land use or soil type in partitioning the sub watershed in different representative hillslopes.

Table IV-9 Fraction of cereal area converted to alfalfa cuttings per sub watershed (%)

Sub watersheds	6	7	8	9
%	25.3	38.1	16.4	34.1

Between 1 and 3 hillslopes in each sub watershed had their land use changed from winter wheat, conventional till management to alfalfa with cuttings. The resulted sediment yield reductions from the changed hillslopes are very substantial as it can be clearly observed on the maps corresponding to each critical sub watershed under two different management scenarios. Looking closely to the figures IV-3 to IV-6, a change in color from red to green is easily noticed, corresponding to a significant drop in sediment yield values generally exceeding 100 t/ha/yr, they are brought under 15 t/ha/yr.

The onsite assessment results of erosion in the critical sub watersheds were also compared in order to appreciate the variation in soil loss amount in the hillslopes where the land use change was conducted. The table IV-10 present in parallel the mapped averaged soil loss results for the treated hillslopes under the current management and the proposed effective management along with the percentage of change. A substantial change (more than 90% reduction) in soil loss for all the hillslope whose dominant land use -cereals- was converted to alfalfa with cuttings

Table IV-10 Variation in soil loss in critical sub watersheds under current and effective management.

Sub watershed	Hillslope Id	Area (ha)	Soil loss(t/ha/yr)		
			Current management	effective management	Change (%)
6	22	70.1	92	4	-95.65
	33	0.6	92.2	5.9	-93.60
	43	9.4	95.1	4.8	-94.95
7	22	47.1	88.9	4.9	-94.49
8	33	13.1	135.9	9.3	-93.16
	43	37.6	183	11.8	-93.55
9	22	34.3	94.5	5.4	-94.29

At the hillslope level, the soil loss rate was brought down the 7 t/ha/yr threshold considered as the soil loss tolerance level under which the agricultural productivity is not compromised, except for the treated hillslopes in the sub watershed 8 where the soil loss rates under effective management exceed slightly 7 t/ha/yr but are far below the 20 t/ha/yr threshold from which erosion rate is considered to be high.(Sadiki et al., 2009)

In the table IV-11, the impact of converting a relatively small fraction of cereal area into alfalfa with cuttings can be observed at the sub watershed level. For a 25% conversion of cereal area into alfalfa in the sub watershed 6, the total soil loss from hillslope has decreased in greater proportion (from 32716.90 t/yr to 17111.90 t/yr) compared to the sub watersheds 7 (from 12790.9 t/yr to 6417.40 t/yr) and 9 (from 15289.7 t/yr to 9721.0 t/yr) where greater fractions were converted, respectively 38.1 % and 34.1 % (see table IV-9).

This suggest that the hillslopes converted in the sub watershed 6, though having a small share in the total sub watershed area, are the main source of the soil lost (see figure IV-3) under the current management (wheat/conventional till) due to other contributing erosion factors like the soil type.

Indeed, most of the remaining hillslopes covered with wheat/conventional till have as soil type; the unit 4 which is less susceptible to erosion compared to the unit 15 and 17. However, in the sub watershed 9, the treated hillslope is not the most exposed to erosion because the two other hillslopes are covered with the soil units 15 and 17.

Table IV-11 Estimated runoff, soil loss and sediment yield in four critical sub watersheds under two different managements.

Sub watersheds	6	6_sc[1]	7	7_sc[1]	8	8_sc[1]	9	9_sc[1]
Runoff	49.80	41.81	55.39	42.83	59.54	54.07	60.96	49.98
Soil lost from hillslopes(t/yr)	32716.90	17111.90	12790.9	6417.40	39177.20	33561.6	15289.7	9721.0
Soil lost from channels(t/yr)	4385.60	6669.80	229.80	360.90	2028.20	7920.5	5.90	9.00
Sediment delivery ratio	0.28	0.37	0.43	0.43	0.31	0.25	0.47	0.46
Avg. Ann. Sediment discharge from outlet(t/yr)	10354.30	8881.10	5585.40	2932.20	12742.90	10447.4	7203.5	4484.6
Area (ha)	316.66	316.66	125.67	125.67	310.14	310.14	100.58	100.58
Avg. Ann sediment yield (t/ha/yr)	32.70	28.00	44.40	23.30	41.10	33.70	71.60	44.60

[1]: sc refers to soil conservation indicating the sub watershed under effective management.

Another pattern captured in the table IV-11 is the general increase in channel soil loss. The reason could be that the water flowing from an alfalfa covered hillslope is clearer, less loaded and has therefore more energy to cause erosion in its adjacent draining channel. The sub watershed 8 stands out with a more than 200% increase in channel soil loss which can be attributed to the fact that the two channels draining the treated hillslopes originates from higher altitude zones and are characterized, due to the steepest slopes, with higher flow velocity which has the potential to cause much more soil loss than in gentle slopes. However due to the great size of the particles detached from a channel and the great length of the channels in the sub watershed 8, the large soil loss amount is not proportionally delivered to the outlet reducing the Sediment delivery ratio (SDR) from 0.31 to 0.25.

For the sub watershed 6 on the other hand, a SDR increase is observed following the land use change. The reason for that variation could be attributed to the proximity of the treated hillslope to the sub watershed outlet. The particles increasingly detached from the draining channel due to the high energy of a less loaded water flowing from the hillslope, are proportionally delivered to the outlet due to the short travelling distance. Therefore, the reduced hillslope's contribution in the sediment discharge amount from the outlet is counterbalanced by the increased channel soil loss amount carried up to the sub watershed outlet. For the sub watershed 7 and 9 however, the great share in the sediment discharge amount from the outlet is by far coming from the hillslopes, the channel soil loss being very small in both management scenarios (see table IV-11) due to the low slope gradient of the channels, (short (for the sub watershed 9) and located in low altitudes. For that reason, the sediment yield varied directly as the total hillslope soil loss contrary to the sub watershed 6 where 47% reduction (from 32716.90 t/yr to 17111.90 t/yr) in the total hillslope soil loss occasioned only 14.37% reduction (from 32.70 t/ha/yr to 28.00 t/ha/yr) in the sediment yield (see table IV-11).

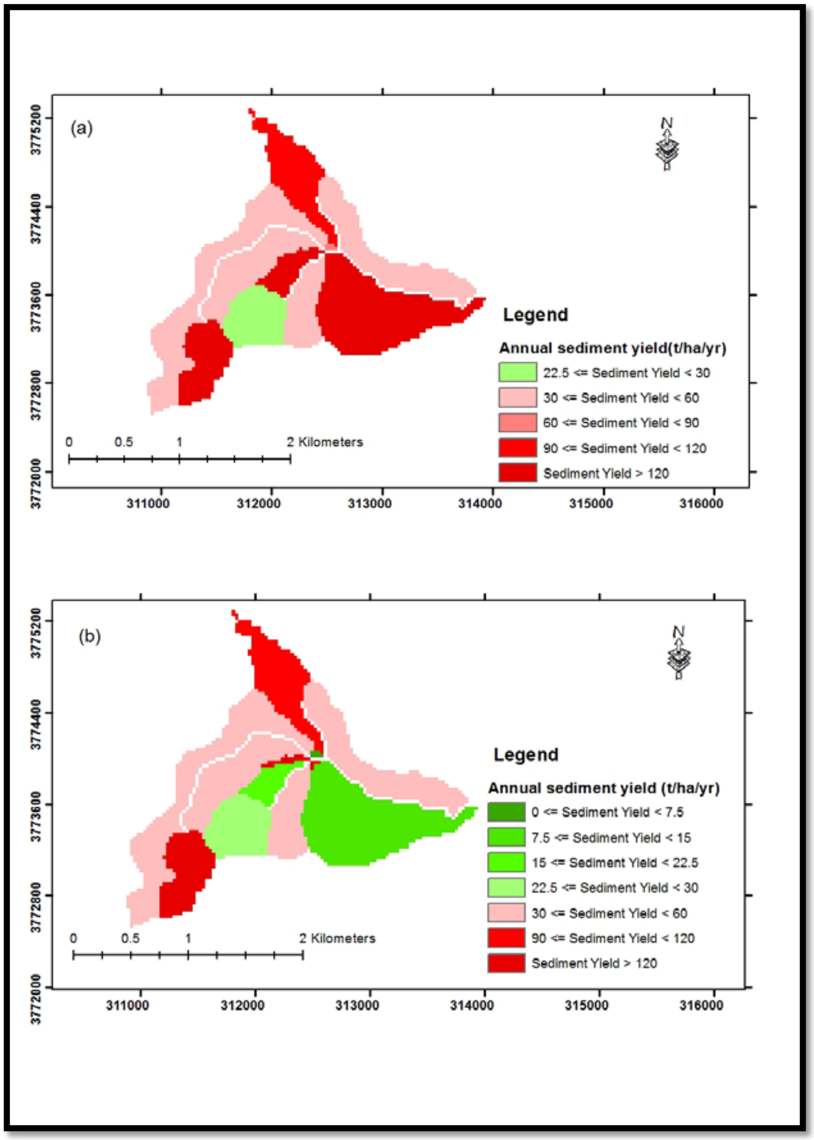

Figure IV-3: Annual sediment yield mapping for the sub watershed 6 without: (a) without alfalfa, (b) with alfalfa

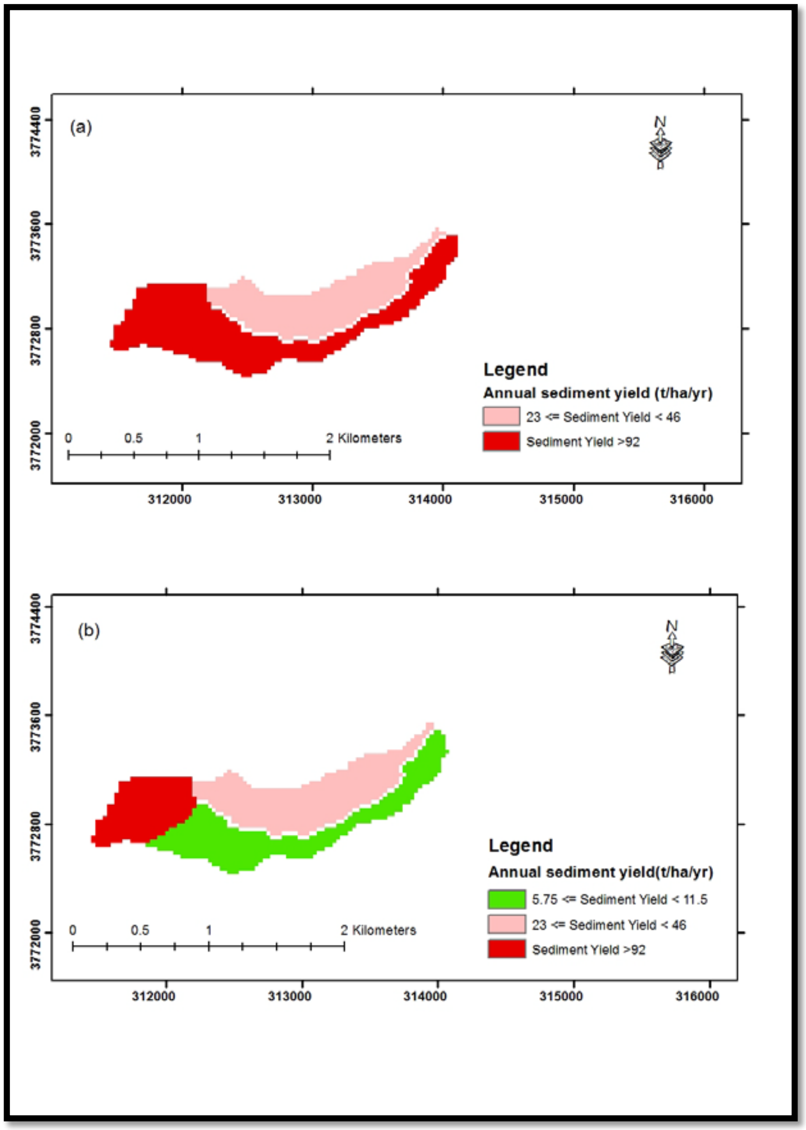

Figure IV-4: Annual sediment yield mapping for the sub watershed 7 without: (a) without alfalfa, (b) with alfalfa

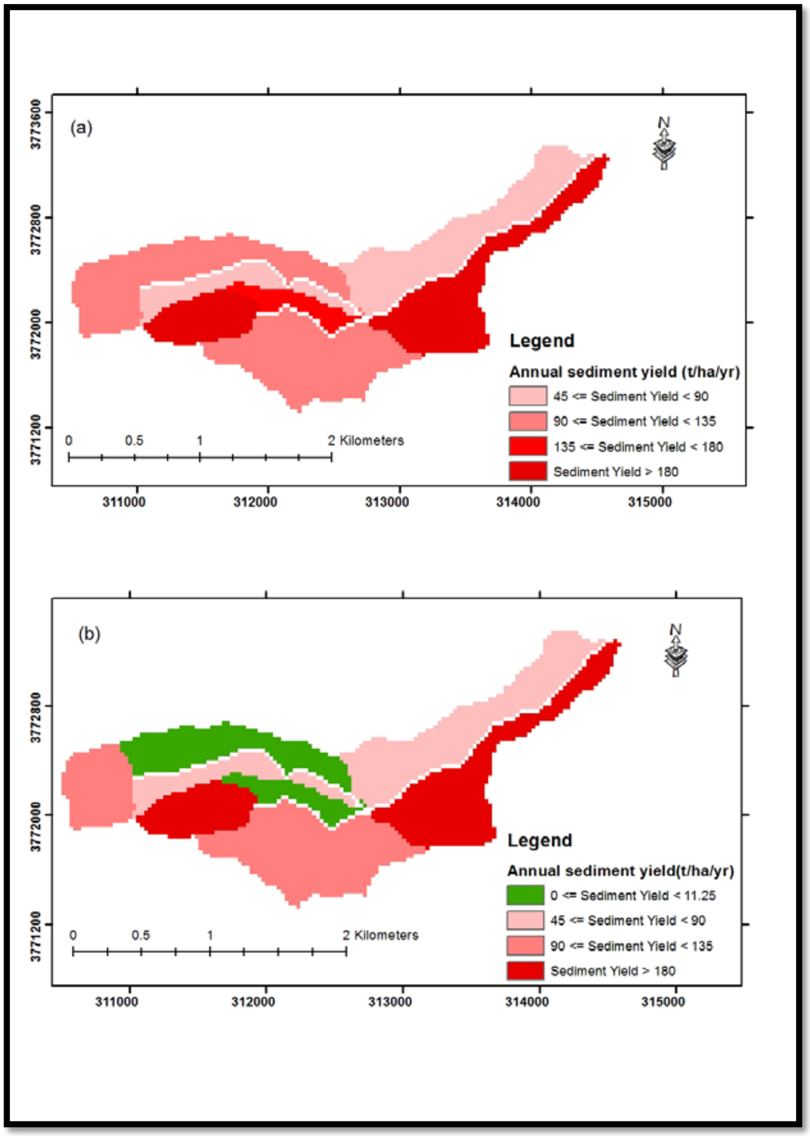

Figure IV-5: Annual sediment yield mapping for the sub watershed 8 without: (a) without alfalfa, (b) with alfalfa

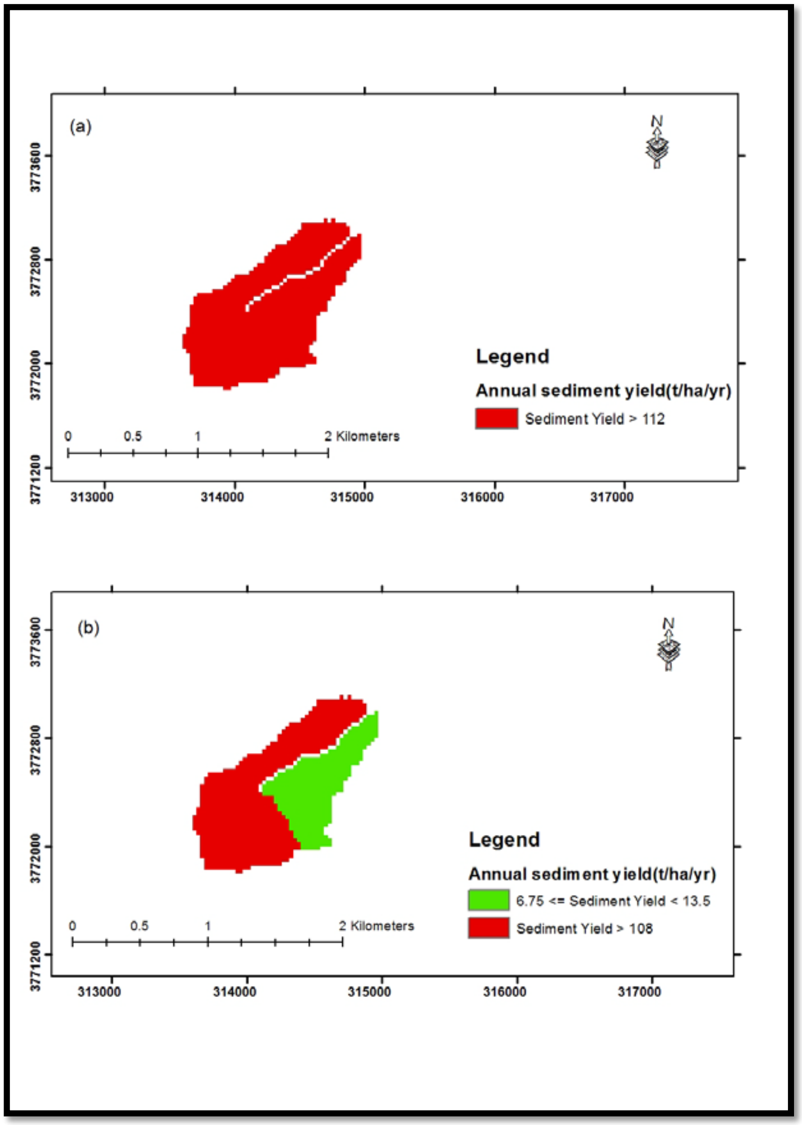

Figure IV-6: Annual sediment yield mapping for the sub watershed 9 without: (a) without alfalfa, (b) with alfalfa

CHAPTER V: CONCLUSION AND RECOMMENDATIONS

Soil erosion is the most important soil degradation process in Morocco and the Rif mountains are the most affected region with the highest erosion rate even worldwide. This environmental issue negatively affects the soil productivity constraining the poor rural population to migrate to marginal lands. Therefore, there is a need of detailed information on soil erosion processes and sediment dynamics at the watershed scale to guide soil conservation planning. In that framework, this study came to contribute to the already undertaken great efforts aiming to quantitatively assess the erosion magnitude in Wadi El Malleh watershed. So far only empirical soil erosion models combined with GIS and remote sensing have been applied to our study area to rigorously map soil loss distribution. However, this methodology although so informing and helpful in soil conservation planning, it does not allow a quick offsite erosion assessment. In this study, the GeoWEPP model, physically-based and continuous simulation soil erosion model was used to bring more insights in the understanding of soil erosion magnitude and sediment dynamics to guide more strategically the soil conservation planning and implementation activities.

The soil units 15 and 17 respectively classified as Vertisol and Calcisol were found to be the most susceptible to erosion among the dominant soil units compared to the unit 4 and C2_316 in the same units. Our study area is highly dominated with agricultural land uses (more than 80%) where the management winter wheat, conventional till is practiced on 70% of the study area. It is important also to note that more than 40% of that management is distributed over the portion of land characterized with soil unit 15 and 17. The result analysis revealed that more than 50% of the zones under cereals (winter wheat, conventional till management) was experiencing soil loss rates above 37.5t/ha/yr which is considered as too high erosion rates in the region. The GeoWEPP limitation to accurately estimate the soil loss and sediment yield values on urban areas, was also highlighted by this study.

An onsite and offsite assessment of erosion were also conducted sub watershed wise. The Sub watersheds were then ranked based on their susceptibility to soil loss and sediment delivery. The sub watersheds 6,7,8,9 were identified as the most critical sub watersheds and prioritized for soil conservation strategy assessment using the GeoWEPP model. The study revealed that more than 90% reduction in soil loss (based on the onsite assessment results) could be achieved if the land use of the targeted hillslopes was changed from winter wheat, conventional till to alfalfa with cuttings. The analysis of the offsite assessment results at the sub watershed level revealed that the reduction in total hillslope soil loss was not proportional to the fraction of cereal area converted to alfalfa with cuttings. We also found out that there was a net difference across the four critical sub watersheds in the way the other parameters were affected by the land use change. We noticed a decrease in runoff across the four sub watersheds in the same proportions as the reduction in percent area under cereals. However, the total channel soil loss increased in the four sub watersheds despite the decrease in runoff and total hillslope soil loss. Even if the increase was not in the same magnitude.

From all the above observations, a lot of insights were gained that could inform better the decision making in terms of landscape management. The use of GeoWEPP model in this study has immensely increased our knowledge and understanding about erosion processes and sediment dynamics at the watershed scale. The model has a lot of functionalities and capabilities not completely exploited here, with the potential to take to another level of performance and efficiency the soil conservation planning and implementation activities. Similar studies should be undertaken in other watersheds of the Rif region and the whole Northern Morocco seriously affected with land degradation, especially where water infrastructures like dams or water treatment are existent to improve their upstream watershed management.

This study recommends that:

1. Runoff/erosion plots be set up across in the different units of the watershed so that a long-term field measurement database can start be built-up for calibration purposes of such models as GeoWEPP.
2. The area under winter wheat, conventional till be converted to alfalfa with cuttings in average proportions wherever the soil type is such as that of unit 15 or 17.
3. Where winter wheat is maintained, farmers shift from conventional till to no till management to reduce the soil disturbance which increases the land susceptibility to erosion.
4. Check dams and filter fences be used to control sediment transport by channels especially in the sub watersheds 1,3,5,6 and 8 where significant amount of soil loss was noted.

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Commenté [A2]: Many references are cited in the text but they are absent in the bibliography list.

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