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Institute of Water and Energy Sciences (Including Climate Change)

A Modeling Approach to Soil Erosion Control and Management using PAP/RAC Model and GIS: A Case Study of Boufekrane Watershed, Morocco

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DECLARATION

I, **KONE Gninwokan Eden Josias** 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.

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CERTIFICATION

This thesis has been submitted with my approval as the supervisor

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ABSTRACT

Erosion by water remains the predominant form of land degradation in the world and accounts for 84% of affected areas. More particularly, the Mediterranean costal region is recognized to be of extreme fragility to erosion. Studies estimated that Morocco agriculture represents almost 20% of its annual GDP, which makes it more concerned with the issue of soil erosion which is recognized to significantly affect crop productivity. The area under study, Boufekrane, is an agricultural area where cultivations (including cereals and tree crops) and other activities such as grazing and livestock account for more than 80% of the total watershed area. The overall purpose of this study was to evaluate soil erosion in Boufekrane watershed located in the eastern part of the plain of Sais (Morocco). Prioritization of the watershed in terms of erosion risk magnitude and expansion trends was made using ArcGIS and qualitative approach called PAP / RAC. It consisted to integrate major causative factors recognized to influence water erosion. In this study, slope, lithology, pedology, vegetation cover and land use were used to assess soil erosion risks. Mapping and overlaying of thematic maps were performed by using ArcGIS software. The assessment of water erosion in this study was carried out in three phases based on PAP/RAC guidelines. The first approach called predictive was aimed at providing preliminary hypotheses for development of erosion risk. It consisted of analysis of natural factors influencing water erosion. The second phase called descriptive consisted to identify current on-site erosion forms that develop in Boufekrane. The consolidation phase, which was the last step, exhibited spatial distribution of erosion risk in Boufekrane by integration and combination of results obtained from the two previous phases. Results indicated that 55.61% of the watershed is affected by sheet erosion, 12.42% is affected by solifluction /sheet erosion. Gully and rills only accounts for 17% of the total surface area of the watershed and are found in areas where slopes and soils are highly sensitive to erosion. The results also showed that cultivation practices, crop types and vegetation cover are found to influence erosion processes in Boufekrane. Effects of slope in water-induced erosion process were found to be of minor degree. The final output map provides a valuable insight for soil conservation planning in Boufekrane and contributes to a more standardized framework of soil erosion control by making findings more applicable and comparable to other watersheds where decision to address soil erosion has been made based on PAP/RAC. In addition, the study can enable the local authorities to prevent from a premature and quick sedimentation of El Gaada dam. However, the model did not consider important data such as rainfall and other climatic data which taints its accuracy in evaluating soil erosion water. Therefore, there is a high recognition to improve PAP/RAC model if one wants it to be an efficient and effective tool for decision-making in soil erosion control and management projects.

Keywords: Boufekrane watershed, soil erosion, risk, PAP/RAC, GIS

RESUME

Les rapports des Nations Unis ont établi que l'érosion des sols est la forme la plus sérieuse des dégradations de terres avec accentuation du problème pour les pays de la Méditerranée côtière dont la vulnérabilité est plus accrue. L'agriculture représentant 20% du PIB national, le Maroc s'en trouve particulièrement concerné par le phénomène d'érosion qui affecte la productivité des sols. Le présent travail s'intéresse à l'érosion hydrique des sols. L'objectif de ce travail était d'évaluer l'érosion hydrique dans le bassin de l'oued Boufekrane situé dans la partie orientale de la plaine de Sais (Maroc), et qui est une zone où l'agriculture est l'activité prédominante représentant plus de 80% de sa superficie totale. La classification du bassin de Boufekrane selon l'intensité des processus ainsi que les tendances de développement érosif ont été réalisées par utilisation de l'approche qualitative PAP/CAR qui se base sur l'intégration des facteurs influençant l'érosion hydrique, tels que la pente, la lithologie et/ou la pédologie, le couvert végétal et l'occupation du sol. La cartographie et la superposition de ces facteurs sous forme de cartes thématiques, ont été réalisées à l'aide du logiciel ArcGIS. L'évaluation de l'érosion hydrique dans le cadre de cette étude a été réalisée en trois étapes conformément aux dispositions et directives données par le PAP/CAR. La première approche dite prédictive avait pour but de fournir des hypothèses préliminaires de développement d'un risque d'érosion. Elle a consisté en une analyse des facteurs naturels influençant l'érosion hydrique et le traitement des bases de données des cartes élaborées. La deuxième étape dite descriptive s'est basée sur l'identification des différentes formes d'érosion constatées dans la zone d'étude. La phase de consolidation qui est la dernière étape a permis d'obtenir une représentation spatiale du risque d'érosion par intégration et combinaison des résultats issus des deux étapes précédentes. Le but est de fournir un produit cartographique précis qui reflète la réalité de l'état de dégradation du sol et l'évolution future de l'érosion. Les résultats ont indiqué que 55.61% du bassin versant est affecté par l'érosion en nappe, 12.42% présente une érosion de type solifluxion / érosion en nappe. L'érosion en rigole et le ravinement ne concentrent que 17% de la surface totale du bassin versant et se retrouvent dans les zones où la pente, et la lithologie favorisent le ruissellement. Les résultats ont aussi montré que les pratiques, les types de cultures ainsi que la perte du couvert végétal accentuent le risque d'érosion. L'incidence de la pente dans le processus d'érosion hydrique s'est avérée de degré moindre. Le produit cartographique final de cette étude constitue un outil pour orienter les décisions en matière d'aménagement du territoire et des méthodes du travail du sol, afin de limiter les risques d'érosion hydrique dans ce bassin et de prévenir la sédimentation prématurée du Barrage El-Gaada. Par ailleurs, l'appréciation des inputs du modèle PAP/CAR a conduit sur la formulation de recommandations à mettre en œuvre si l'on veut améliorer sa performance dans l'évaluation des phénomènes érosifs dans l'ensemble des pays de la Méditerranée côtière.

Mots clés : Boufekrane, risque d'érosion des sols, Modèle PAP/RAC, GIS

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DEDICATION

Every challenging work requires personal commitment and efforts, but it also calls for guidance of elders especially those who are very close to our heart.

My LORD and GOD JESUS-CHRIST, who strengthened and guided me throughout my studies.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACB	Albania Coordinating Board
DRCL	Direction Régionale des Collectivités Locales
GDCN	General Directorate for the Conservation of Nature
ETP	Potential evapotranspiration
ETR	Actual evapotranspiration
ECDGENAS	European commission DG Environment News Alert Service
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GLASOD	Global Assessment of the Status of Human-Induced Soil Degradation
ITPS	Intergovernmental Technical Panel on Soils
MAP	Mediterranean Action Plan
PAP	Priority Action Plan
RAC	Regional Action Plan
SRBA	Sebou River Basin Agency
SRTM	Shuttle Radar Topography Mission
UNEP	United Nations Environment Programme

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UNITS

(m) ……………………………………………………… Meter

(mm)……………………………………………………. Millimeter

(ha)……………………………………………………… Hectare

km^2……………………………………………………...Square kilometer

t/ha/yr…………………………………………………… Ton per hectare per year

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

Soil in good plays an important life to sustain life as it contributes to ecological and environmental balance. It can also serve as a vegetal support for food and medicinal plants necessary for the well-being of human beings. According to PAP-RAC (1997), it takes 100 years for 1mm of soil to form. In other words, it takes centuries, millennia or even longer periods for lands to form. However, soil degradation by erosion can occur in only a few years, a few months, a few days or even a few seconds, in extreme conditions of droughts or floods. As recognized by Larson *et al*. (1983), concern over erosion is universal affecting all the countries. Erosion by water is defined as a wearing-away of soil through a process of detachment and/or transport of soil particles by erosive agents which are in most cases water in form of either raindrop or overland flow runoff (El-Swaify *et al.*, 1982; Morgan, 2005). Investigations of PAP/RAC on a report by United Nations showed that water-induced soil erosion remains the predominant form of land degradation and destroys 84% of affected areas (PAP-RAC, 1997). Moreover, studies by FAO showed that worldwide, 5 to 7 million hectares of land valuable to agriculture are lost every year through erosion and degradation (FAO and ITPS, 2015). In 1990, GLASOD reported that nearly one-sixth of the world's vegetation has suffered land degradation of varying degrees in the last 50 years. In Africa, soil erosion significantly affects developing countries especially those bordering the Mediterranean Sea (Morgan, 2005). According to Sarraf and Croitoru (2010), decline in soil productivity in Africa is estimated between 2% and 40%. Moreover, most of African countries have their economies that strongly rely on agriculture and therefore, are found to be vulnerable to soil erosion (Morgan, 2005). African countries of the Mediterranean are particularly affected by erosion (Sarraf & Croitoru, 2010). Several studies have showed the high vulnerability of the Maghreb region which is characterized by abundant sloping lands, dominance of rain fed agriculture, important alternation of long dry periods and heavy rainfall and rapidly growing population which has increased by 300% since 1950 (Lynden and Oldeman, 1997; Raissouni *et al.*, 2012; Puigdefabregas and Mendizabel, 1998). Erosion in Morocco is expected to increase in magnitude if no anti-erosive measures are implemented (Kefi *et al.*, 2011). PAP/RAC (2005) reported that Morocco agriculture accounts for almost 20% of its GDP. It goes to say that irreversible and irreclaimable loss of lands will be prejudicial for Morocco economy. In a country where almost 20% of the rural population live in mountainous areas and cultivate more than 500,000 ha of forests, non-sustainable agricultural practices are highly likely to take place (DGCL, 2015). PAP/RAC (2005) reported that erosion by water affects 40% of Morocco's lands with an annual soil loss estimated between 500 and 600 million t/ha/yr. Soil erosion is also recognized as one of major challenges that developing countries will face in the 21st century (Lal, 2001). According to Raissouni *et al.* (2016), Morocco is amongst the Western Mediterranean countries that suffer at most from soil erosion, which exceeds all international standards putting the country in a critical situation. Negative effects of soil erosion are perceptible on soil productivity with important loss of soil, organic matter and soil retention (Kefi *et al.*, 2011). It also intensifies soil mineralization, active erosion notches and progressive salinization of irrigated lands (*ibid*). In long term, Morocco can be severely affected by food insecurity if no erosion control programme is undertaken. Moreover, the problem of soil erosion in Morocco is a threat to its environment and ecology which already exacerbated by desertification and climate change impacts recorded in the last decades (Bhattarai & Dutta, 2007). Although it is impossible for erosion to be avoided as it is a natural process, it can however be identified, assessed and limited to a maximum acceptable level or soil loss tolerance (Morgan, 2005). Unfortunately, efforts and attempts to control and manage soil erosion are in most cases inefficient due to inability of designed plans and actions to target the real causes (PAP-RAC, 1997). In addition, application of different erosion assessment initiatives in Morocco makes land management programmes at national and regional scales difficult (*ibid*). Assessing soil erosion in Boufekrane by application of PAP/RAC model will contribute to demonstrate its applicability in Moroccan conditions, in a view to promote it as a suitable soil erosion assessment methodology for all Morocco.

1.2 Problem Statement

The area under study, Boufekrane, is an agricultural area where cultivations (including cereals and tree crops) and other activities such as grazing and livestock account for more than 80% of the total watershed area (Hayat, 2017). In a recent study, Ouazzani (2008) reported that soil losses due to erosion in Boufekrane watershed on average were as follows: 11.56 t/ha/yr for irrigated scheme, 17.07 t/ha/yr for olive, 28.79 t/ha/yr for cereals and 9.21 t/ha/yr for non-cultivated lands. Moreover, it is proved that erosion affects productivity of crops and leads in long term to soil fertility decline (Lal, 2001; Larson *et al.*, 1983; PAP-RAC, 1997). The increasing population, climate change impacts, climate variability along with important fluctuations characterized by extreme conditions of droughts and heavy rainfall in the region of Fez-Meknes where Boufekrane is located make it more vulnerable to erosion (Raissouni *et al.*, 2016; Nicholls and Hoozemans, 1996; DGCL, 2015). Moreover, in Boufekrane watershed, there is a dam called El Gaada covering an area of 12.28 ha. In absence of implementation of measures that can help stemming erosion in Boufekrane, the current situation although on control can worsen and lead to high costs of land restoration, severe vegetation cover destruction or even in the worst of scenarios result into irreversible land degradation. All this can significantly affect sustainability of farmlands and agricultural activities in Boufekrane watershed: Effects will be felt on crop productivity, livestock production through loss of animal weight, water quality degradation and forage potential. Acknowledging the importance of erosion risk assessment in efficient decision-making for land management, one witnessed a prolific development of models, initiatives and approaches to evaluate water-induced erosion over this century (UNEP, 2000). However, this multiplicity of initiatives causes a lack of coordination and between approaches, which often make development projects at national and regional level difficult. Assessing soil erosion in Boufekrane by application of PAP/RAC model will help to contribute to a more standardized framework that will make control and management measures in other areas of Morocco comparable and applicable to Boufekrane case study.

1.3 Justification

It is widely recognized that Mediterranean soil degradation is mostly caused by water (UNEP, 2000). *Figure 1-1* shows that in Morocco, rainfall-induced erosion of moderate to extreme level covers almost half of its total area. Besides, it is asserted that Boufekrane is mainly dominated by agriculture activities which cover more than 85% of its total area (El Garouani, 2017). Olives, cereals and fruits are the most cultivated crops (*ibid*). The United Nations reported that erosion significantly affects crop yields (UNEP, 2000). Furthermore, Stocking (1986) carried out an analysis on detritus formation where he found out that soil swept by water through erosion contained more nutrients than the soil of origin with a nutrient enrichment ratio estimated to 2.5. In addition to that, UNEP (2000) found that losses in concentration of nitrogen and phosphorus through erosion were three times higher than total amount of fertilizers applied at crop growth stage. In such a context, soil erosion can entail a huge financial cost given the importance of agriculture in Morocco and more particularly in Boufekrane. Assessing and mapping soil erosion risks in Boufekrane watershed can be a basis for implementation of soil conservative strategies and efficient erosion control tool for farmers as to enable agriculture sustainability and prevent from crop productivity decline and livestock production reduction as a result of soil erosion (Kadomura, 2001). The qualitative output map that will exhibit from PAP/RAC methodology will provide farmers, practitioners, decision makers and conservationists to more understand soil erosion processes and expansion trends, as to implement effective and efficient control measures (ACB, 2002; PAP-RAC, 1997). Moreover, it is a good management tool that can enable the local authorities to prevent from a premature and quick sedimentation of El Gaada dam.

Table 0.1: Land use in different Mediterranean countries (MAP/PAP, 2000)

Degradation type		**Spain**	**Morocco**	**Italy**	**Tunisia**	**Turkey**
Water erosion	Extreme	3.0	6.0	0.5		22.3
	Strong	49.0	12.2	35.0	37.0	36.4
	Moderate	12.5	25.7	47.5		20.0
	Light	25.5	9			7.2
Wind erosion	Extreme					
	Strong		1.0			
	Moderate		16.0			
	Light					
Physical degradation	Extreme					
	Strong			14.0		2.0
	Moderate					
	Light					
Lakes	Light				0.5	
Chemical degradation	Extreme					
	Strong	6.0				
	Moderate		12.4*			
	Light	1.0	13.4			
Stable terrain under natural conditions		3.0				
Salt flats					6	
Dunes or desert			4.2		19	

** The area is a desert area*

1.4 Objectives

1.4.1 General objective

The main objective of this study is to evaluate soil erosion risks in Boufekrane watershed by application of PAP/RAC methodology.

1.4.2 Specific objectives

The specific objectives of this study were to:

a) determine the potential erosion from Boufekrane watershed
b) evaluate the actual erosion state in Boufekrane watershed
c) establish spatial distribution of erosion risk in Boufekrane watershed

1.5 Research Questions

In order to assess the specific objectives specified above, the particular study examines the following questions:

- What is the potential of water-induced soil erosion of Boufekrane watershed?
- What are the current erosion forms that occur in Boufekrane watershed?
- How is erosion risk spatially distributed in Boufekrane watershed?

1.6 Scope and Limitations of the Study

There exists a wide range of soil erosion types according to the nature of erosive agents involved in the process. This particular study only focuses on physical erosion especially on water-induced erosion that affects soils in Boufekrane watershed. PAP/RAC methodology and GIS are used to evaluate erosion by water. Furthermore, the present study framework is a modelling approach to soil erosion control and management. Therefore, it does not explore conservation measures to be implemented as means to control soil erosion. However, the findings obtained from this study can serve as a basis for implementation of soil erosion control and management policies in Boufekrane watershed.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

It is undeniably true that erosion has considerable negative impacts on the economy of countries. Numerous studies assessed the loss of soil nutrients due to erosion. It is estimated on average that every year, 23 to 42 million of tonnes of Nitrogen and 15 to 26 million of tonnes of Phosphorus are lost through erosion (PAP/RAC, 1997; UNEP/MAP/PAP, 2000; FAO, 2015). Loss of those nutrients is compensated by fertilizer importations involving huge financial costs. Moreover, impacts of soil erosion on environment have been seriously discussed among scientists and conservationists. Morgan (2005) approached water soil erosion as a two-phase process of soil particles detachment from the soil mass and their transport by water. Numerous studies attempted to find factors that influence and exacerbate rainfall-induced soil erosion. As remarked by Morgan (2005), soil erosion depends not only on physical and climatic factors such as rainfall, slope, vegetation or soil cover, but also on anthropogenic practices. Lal (2000) discussed the link between socio-economic and political factors and soil erosion process intensification. FAO and ITPS (2015) stated numerous reasons why soil erosion is not well integrated with developments plans. One of them was that processes of soil formation and changes are quite longer which make governments and policies to not act until soil problems worsen to a critical point. Another argument is that in majority of countries, decision makers do not have sufficient insights in soil erosion impacts because of lack of credible and conclusive evidence needed for a decision-making. All this calls for both soil erosion control and land degradation prevention which will significantly contribute to climate change mitigation. Lal (2001) assessed contribution of soil erosion control in C sequestration of plants by roots, which in turn can reduce CO2 emission in atmosphere (Gomiero, 2016; Price *et al.,* 2015; Morgan, 2005). At local scale, the consequences of soil degradation on farmers range from decrease of soil fertility to major soil losses, as well as pollution and turbidity of water courses (Montgomery, 2017; Lambin *et al.,* 2013; Sarraf & Croitoru, 2010; Zalidis *et al.,* 2002). There exists a wide range of methods, models and software used to assess and model erosion risks as well as actual erosion. Universal Soil Loss Equation (USLE) and its revised version (RUSLE) are the most used models to assess soil erosion and become the major soil conservation planning tool in the world given that to their simplicity and applicability to different situations. Lal (2001) recognizes necessity to have standardized soil erosion assessment.

2.2 Causes and Factors of soil erosion

2.2.1 Rainfall

Climate intervenes in erosion processes through rainfall and at minor extent temperature. Rain is recognized as an essential agent of soil erosion (Kinnell, 2005). El-Swaify *et al.* (1982) reported that countries in humid tropics lying between latitudes 40° N and 40° S and characterized by heavy annual rainfall are found to be the countries that suffer at most from erosion by water. Soil erosion occurs when soil is exposed to rain drop energy. Kinnell (2005) found that erosion by water results from expenditure of raindrop and water flow energies which cause detachment and transport of soil aggregates. Other studies have shown that there is no relationship between rainfall amount, runoff and land loss (Van Dijk *et al*., 2002). However, rainfall intensity and kinetic energy were found to be the most important factors in erosive action of rains (Van Dijk *et al*, 2002) . (Salles *et al*, 2002) recognized that rainfall kinetic energy is a factor that is widely used to express the power of rainfall to detach a soil. They reported different relationships between rain kinetic energy (KE) and rainfall erosivity (I) (Gilley & Finkner, 1985; Salles *et al.*, 2002).

2.2.2 Pedology

FAO and ITPS (2015) reported that soils with high content of clay have a low erodibility which is due to their resistance to detachment. Far before, El-Swaify *et al.* (1982) investigated on different soil types and their susceptibility to erosion. They found out that erodibility factors were different from one to another and that, those differences accounted to their peculiar texture, structure and mineralogy characteristics. It was also found that coarse texture particles make soils resilient to erosion because they are carried away by water with difficulty although they can easily be detached by it. Soils with high content of silt are the most erodible soils. Those soils are easily detached, which makes their particles more susceptible to transport by water. FAO found that soils with high organic matter content tend to be less erodible. Le Bissonnais (1996) assessed the role of organic matter in increased infiltration, which in turn reduces risks of soil detachment by runoff. Soil depth is also found to have significant effects on soil erodibility.

2.2.3 Vegetation cover loss

Annually, it is reported that loss of vegetation cover causes a soil loss exceeding 15 t /ha on more than one third of total arable land in the Mediterranean basin (UNEP/MAP/PAP, 2000). In attempt to assess impacts of vegetation cover decline on intensification of soil erosion processes, Walling (1999) reported that most erosive processes develop in areas where vegetation has been considerably reduced. Similar findings exhibited from another study. According to Verstraeten (2003), decline of vegetation cover increases runoff on sandy soils even under low steep slopes and rainfall. Lynden and Oldeman (1997) stated that conversion of forested lands into agricultural areas is considered as a major factor of land degradation and erosion process acceleration. It was also shown by various that a well-developed vegetation cover protects the soil from rain erosive action. Indeed, vegetation cover minimizes erosive effects of raindrops on soil by roots trapping particles in a dense root system. Vegetation therefore increases soil resistance to shear forces and limits its incision. Gyssels *et al.* (2005) reviewed and compiled numerous studies show important role of roots on soil cohesiveness.

2.2.4 Impact of cultural practices

According to Zalidis *et al.* (2002), soil compaction and erosion are the most widely spread effects of unsustainable practices in the Mediterranean. He found that soil compaction is a result of use of heavy farm machines. Consequently, runoff is increased which makes soil more vulnerable to transport. Lynden and Oldeman (1997) summarized different agricultural activities that are susceptible to cause land degradation, thus soil erosion:

- Intensive use of fertilizer inputs;
- Interruption of soil protection measures;
- Intensive use of heavy machinery for plowing and compaction;
- No observation of fallow periods in shifting cultivation systems;
- Irrigation water of poor quality

In addition, overgrazing along with soil trampling and vegetation cover loss as a result of livestock, are found to increase erosion in a given area (*ibid*). Abahussain *et al.* (2002) support that intensification of agriculture associated with cultivation on marginal lands and poor management practices are major factors of rapid soil erosion expansion and desertification in arid region. Moreover, United Nations conducted a study whereby it was shown that intensified land use can reduce the resilience of soil to soil erosion and land degradation (Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, 2015b). Walling (1999) demonstrated that conversion of natural areas like forests into cultivated areas can significantly increase erosion by an order of magnitude or even more.

2.2.5 Anthropogenic factors

Among the direct causes of soil erosion in the Mediterranean, deforestation resulting from abusive cutting of trees should be considered as a major influencing erosion factor (Lynden and Oldeman, 1997; FAO, 2015). In Morocco, pastoralism is viewed as an important activity as presented in table 2.1. In this context, reduction of grazing areas due to soil erosion and shift to agriculture with reconversion of available lands have significant impacts on increased soil erosion: loss of pasture and rangeland areas implies an increase of animal pressure on lands which, in turn, leads to important removal of arable lands and progressive soil degradation. Additionally, population increase associated with rapid conversion of forested lands into tourism and recreational areas as well as intensified urbanization and generalized bush fire contribute to increase soil erosion process. Paradoxically, rural exodus can all the same contribute to increased soil erosion in the Mediterranean by abandonment of soil conservation infrastructures in rural areas.

Table 0.1: Land use in (Source: (UNEP/MAP/PAP, 2000)

Cultivated areas (%)	Forest (%)	Grazing (%)	Others
21	20	47	12

**'Others' refers to non-productive lands including desert areas.*

2.2.6 Lithological factor

Parent rock materials are important factors that determine vulnerability of a soil to erosion. The various types of rocks and their structure give a valuable indication of soil infiltration capacity. Therefore, lithological characteristics of a soil furnish details on amount of soil that is sensitive to erosion (Krynine and Judd, 1957; Demmak, 1982). Low infiltration of flushing rocks indicates that a large amount of water is trickling, therefore a large amount of soil can be washed away. Wischemeier *et al*. (1971) was able to show that the intrinsic erodibility of soils can be determined on the basis of their analytical characteristics. The latter have defined a monogram which makes it possible to calculate the factor "K" of erodibility, which is according to:

- Content of organic matter;
- Texture;
- Structure;

- Permeability;
- Percentage of fine earth or coarse elements.

2.2.7 Slope factor

Researchers worldwide agree on the major role played by topography in rainfall-induced erosion processes. Slope can accelerate erosion processes especially at high rainfall intensity as recognized by Qadir (2014). On very erodible geological substrate, detaching forces acting on soil particles increase with slope. The slope greatly influences the importance of erosion but the existence of erosion and intense runoff on gentle slopes indicate that there is no need for a steep slope to trigger this phenomenon (Fauck, 1956; Fournier, 1967). Battany and Grismer (2000) investigated on effects of slope on erosion processes: They showed that there was a strong correlation between the two variables at a confidence interval of 0.95. Slope influences erosion process by its shape, gradient and length Qadir (2014).

a) Slope shape

According to Qadir (2014) and Gray (2016), concave slopes generate less soil loss than planar or uniform slopes. In addition to that, Şensoy and Kara (2014) built their findings upon studies of Young and Mutchler (1969). They reported that under the same slope steepness conditions, a convex and uniform slopes generate more sediments, thus induce more soil loss than concave slopes (Şensoy & Kara, 2014). Rieke-Zapp *et al*. (2005) carried out a similar study whereby sediment yields were simulated under different slope shape conditions including concave, linear and convex slopes. Results indicated similar findings. For concave slopes, soil losses are greater next to the point upstream of the slope and decrease to the point where the slope becomes critical (Gray, 2016; Şensoy & Kara, 2014). Tilting is critical as soon as sediments begin to form. For convex slopes, erosion gradually increases towards the downstream slope (Gray, 2016).

b) Slope inclination

While coming across with effects of slope gradient on soil loss, Fox and Bryan (2000) as well as Assouline and Ben-Hur (2006) recognized that impacts of rainfall on soil erosion are substantially aggravated by slope gradient. As the gradient of slope increases, the kinetic energy of the rains remains constant but soil transport accelerates downwards. This accounts to the increase of runoff kinetic energy. Fox and Bryan (2000) supported that slope inclination significantly increases rill erosion intensity. Moreover another finding of Fox and

Brian (2000) was that soil loss increase can be expressed as a square root function of slope inclination. When slope increases, the inclined surface exposed to rain is higher because of the slope steepness (Assouline & Ben-Hur, 2006). Obviously, when the slope is low, runoff energy is not sufficient enough to carry coarse sand particles. Mcisaac *et al.* (1987) observed soil loss from disturbed lands and found that soil loss due to slope steepness is substantial.

c) Length of the slope

In principle, the longer the slope the more runoff accumulates. Although researchers fail to agree on impacts of slope length on soil loss, one can argue that long slopes induce important total runoff volumes that are found to increase soil loss risks. Paradoxically, El-Swaify *et al.* (1982) found that the amount of runoff per unit area is less on long slopes than on short slopes. Zing (1940) found a relationship between slope length and soil loss. Zing's findings were taken up by El-Swaify *et al*. (1982) and Liu *et al.* (2000) who reported that that soil loss can be expressed with respect to slope length as follows: $E = b.\gamma^{m}$ where E is the soil loss, $\gamma(m)$ the slope length, b and m are empirical coefficients.

2.2.8 Mechanisms of Soil Erosion by Water

As mentioned earlier, soil erosion process involves two phases: detachment and transport (Morgan, 2005; Gilley & Finkner, 1985). However, several other researchers argue that soil erosion is a three-phase process: detachment, transport and deposition of soil. The last phase occurs when transport energy is no longer available (Lal, 2001). Kinnell (2005) classified detachment and transport processes into four major categories according to the erosion acting agent that predominates. He distinguishes: Detachment induced by raindrop with material transport induced by raindrop splash (RD-ST): It occurs when the critical raindrop energy that causes detachment is attained but there is no surface water yet to transport soil particles. Raindrop detachment with splash-induced flowing transport: It occurs when the soil is detached by raindrop and flowing water carries soil materials. In this scenario, raindrops penetrate through the stream to detach soil particles. Water flows that develop on soil surface are helped in soil transport process by raindrop splash effect which after detaching particles from the soil, lift the particles in the flow. The resulting transport process implies both impact of raindrop and flowing water, hence the name "Raindrop-Induced Flow Transport (RIFT)". RIFT is a more efficient transport system than RD-ST, but requires more flow energy to transport soil material. Detachment by raindrop with Flow water Transport (RD-FT): In this case, particles are detached by raindrop impacts and transported downstream by water flows without raindrops are involved in the transport process. This RD-FT detachment transport system is more efficient than RD-RIFT. In most cases, both systems RD-RIFT and RD-FT occur simultaneously in the same stream where the latter deals with fine particles whereas RIFT deals with coarse materials. Flow Detachment and Flow Transport (FD-FT): Both detachment and transport are induced by flowing water.

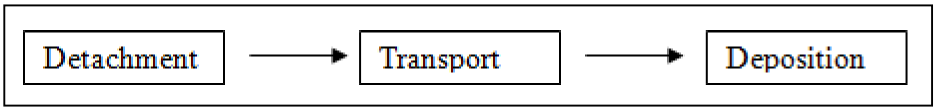

Figure 0.1: Soil erosion processes

a) Detachment by water

For soil to be transported, it has to be in a detached condition beforehand (Lal, 2001). Detachment is therefore a major factor of erosion determining whether erosion process can occur or not. According to Kinnell (2005), erosion occurs only if soil materials are detached. He also found that detachment is a result of two agents acting individually or simultaneously: Raindrop and runoff. Detachment process is driven by rain splash impact. Le Bissonnais (1990) distinguished different scenarios describing soil detachment process intensity in relation to raindrops. He found out that raindrops as soil detaching agents have important effects when soil is dry and the rainfall intensity is high, with contrast to situations where soil is initially wetted or saturated with relatively lower rainfall intensity. In the same way, Morgan (2005) supports that the more the soil receives cultivation practices, the more it is vulnerable to detachment process that becomes more important. Cruse and Larsen (1977) pointed out that rain splash detachment is function of soil structure and its shear forces. Detachment process is found to decrease with increased soil shear forces (Morgan, 2005). As Ellison (1945) remarked, when raindrops fall on soil, they break down and separate particles and aggregates into individual grains. He found that Magnitude of detachment and transport processes of soil particles depend on both kinetic and potential energy of rain splash (Ellison, 1945). The kinetic energy of a raindrop is function of its mass and the square of its velocity.

b) Transport by water

In transport process, soil is carried by overflow and interflow runoff. Similarly with detachment, transport of soil can also result from a combined or individual action of rain splash and overflow. Once soil particles are detached, they are entrained by flowing water and transported until transporting capacity of flow becomes negligible. This process occurs when transporting forces are higher than forces retaining the particles. Lal (2001) found that the more the soil is devoid of vegetation cover the more important are those carrying forces. Meyer and Wischmeier (1969) found that there is a close relationship with the velocity of the flow (Morgan, 2005).

2.3 Historical Context of the Mediterranean: Vulnerability to Soil Erosion

Before colonists settled and started educating on ecological behaviours, Mediterranean indigenous people used to exacerbate forests for cultivation purposes allowing destructive practices that posed a threat on environment (Butzer, 2005)**.** However, several other researchers object to this point of view and do not side with this argument. Huntington (1910) supported that forest decrease in Mediterranean region is mainly due to rainfall shortage. Further research has showed limits of such arguments and point out that Mediterranean soils have been seriously eroded by high rainfalls owing to abnormal climatic conditions (*ibid*). According Butzer, fragility of Mediterranean soils partly derived from detachment of an important amount of sediments on high slopes. The author also argued that proneness of Mediterranean soil to erosion resides in replacement of some ethnic groups and populations. For instance, erosion processes later than 600 CE started to develop with resettlement of Slavs and Albanians, accompanied by introduction of different ecological behaviours. For Zalidis *et al.* (2002), fragility of the region has been aggravated by diverse factors: increase of land pressure by migration, adoption of cash crops and new technologies. Another contribution in the area of Mediterranean vulnerability assessment was made by Abahussain *et al.* (2002). They found that areas affected by desertification in the Maghreb were estimated to 3,108,420 km^2 (Abahussain *et al*., 2002). They also found that desertification expansion in that region was mainly due to sand dune transport into rangelands (*ibid).* According to Zalidis *et al*. (2002), vulnerability of Mediterranean region to sheet and gully erosion is partly due to its relief: Dominance of mountains and hills make the relief unstable and highly prone to erosion, with a greater intensity of vegetation absence. Agriculture activities in the Mediterranean has been found to intensify during Muslim and Christian settlement (Butzer, 2005). As a result, soil erosion significantly developed during the second half of Muslim occupation (ibid). Moreover, Mediterranean agriculture has been revolutionized by adoption of arboriculture (tree crops such as olive and grape) (Butzer, 2005). As a result, new systems of cultivation were invented to deal with development of such tree crops, which in most cases grow on steep slopes. (Abahussain *et al*., 2002) reports that agriculture was mainly dominated by subsistence farming and grazing before introduction of new agriculture forms in the middle of the 1900s so as to face increase of food demand. Intensification of agriculture led to important environmental hazards such as floods and extreme droughts (Butzer, 2005). Later on, fruit cultures were introduced (*ibid*). Further innovations for more efficient practices were introduced. Intensive use of new forms of technologies in agriculture entails important environmental damages including adversely soil erosion issues (Butzer, 2005). In addition to that, one can argue implication of combined factors of recurrence of climatic anomalies characterized by persistent extreme rainfall conditions, with population growth, political instability and migratory movements in impeding and challenging soil control and management measures (Butzer, 2005). According to Butzer (2005), change of agricultural practices in Mediterranean regions may have reduced soil protection level. Erosive practices such as deforestation, cultivation of olives and grapes on steep slope hillsides, cultivation on marginal rangelands have led to increase in runoff, infiltration water decrease and obstruction of wetland channels (Abahussain *et al.*, 2002; Butzer, 2005). Besides, overgrazing has been for ages a major factor of land degradation (Nicholls ands Hoozemans, 1996; PAP/RAC, 1997; UNEP/MAP/PAP, 2000).

2.4 Forms of Erosion

Several erosive systems are evident depending on surface condition, soil morphology and rainfall intensity. A soil exposed to intense rainfalls can develop diffuse erosion. A previously beaten soil produces a low-level runoff that produces linear erosion. On cultivated plots, concentrated runoff gives rise to modest-sized forms, which generally widen when the soil is devoid of vegetation. The terminology is based either on the depth of the channels or on the comparison of channel profiles with the neighbouring terrain. It is thus possible to distinguish:

2.4.1 Sheet erosion

Sheet erosion is not well documented because of its relatively minor impact on soils. According to Kinnell (2005), sheet erosion is one of the most recurrent forms that affect agricultural areas. It is defined as a slight removal of soil layer due to either rainfall or wind energy effect (Morgan, 2005). Kinnell (2005) found that sheet erosion is mainly caused by raindrop splash. According to (Dehne, 2015), wind-induced sheet erosion is not very apparent especially at its starting development process. Sheet erosion by water forms as water flows and detaches and carries thin soil layer. Studies have showed that sheet erosion can become important as slope increases (more than 1% to 2%). It was also found that stabilization is one of the efficient methods that can help preventing from sheet erosion formation. Although channels of sheet erosion are small, they can develop and enlarge as runoff increases or vegetation cover reduces. The displacement of the particles takes place first by splash effect at short distance and then by surface runoff: during the rainfall, fine particles (clays, fine sands, silt, organic matter) will leave the wetted clods to settle in the hollows and puddles; They are then taken up by surface runoff to form pellicle crusts of sediments that greatly reduce infiltration, favouring runoff. The entrainment of the fine particles by the water streams and the washing by the sheets, leaving towards the end of the downpour of the superficial pavements (coarser elements left on the surface: coarse sand, gravel, etc ...). Soil erosion is selective erosion; It is thus considered to be a major factor of soil degradation and impoverishment. In addition to fine detritus materials, surface runoff carries light particles: organic matter, crop residues, animal discharges.

2.4.2 Rills

According to Morgan (2009), rill formations are influenced by topographic, vegetative and agricultural practices conditions. Loch (1979) suggests that rill is the most serious erosion form in sloping cultivated lands. It is a slight incision which mostly develop on very steep slopes in the form of small channels with depth estimated to some dozen of centimetres (Morgan, 2005). It was found that sediments yields transported by rill erosion are for far more important than sediments yields carried by sheet erosion (Loch, 1979). Normally, rills are masked by tillage operations. He concluded that while measuring rill-induced sediment rate change, one should consider more its variation to time rather than the total sediment yields.

2.4.3 Gullies

This is the most serious form of soil erosion. Poesen *et al.* (1996) suggested that gully is a steep-sided furrow that is mostly caused by intermittent flow of water. According to Verstraeten (2003), it can be defined as removal of soil as a result of water runoff and over short duration. Hauge (1977) suggested critical criteria that can best characterize gullies. He supported that gullies can be characterized by a cross-section area greater than 929 cm^2 (Poesen *et al.*, 1996 ; Morgan, 2005). Studies showed that gully erosion results from poor management practices and excessive vegetation removal. Research has shown that uncontrolled rill can develop and give gully (Natural Resources, 2006). However, gully width is smaller than that of rill, but the latter is shallower than gully (Morgan, 2005). Verstraeten (2003) reported that gullies contribute between 10% to 94% of total sediment yields a result of rainfall-induced erosion. It was also found that in the Mediterranean, soil losses due to gully erosion are more important in abandoned crop lands (Poesen *et al.*, 1996).

2.5 Consequences of Uncontrolled Soil Erosion

2.5.1 Loss of arable land and loss of soil fertility

Decline in soil fertility is not exclusively a direct consequence of erosion (figure 2.2). (FAO, 2015) investigated on numerous possible factors of soil fertility loss and found that the latter can result from intensive agricultural practices (fertilization, tillage operations, deforestation), chemical pollution (acidification). For El-Swaify *et al.* (1982), intensive land use can substantially trigger a loss of fertility. However, other studies have focused on the role of soil erosion in soil fertility decline. For instance, Morgan (2005) and ECDGENAS (2014) assessed impacts of erosion and showed that soil erosion carries away important nutrients for plants through transport. The same findings were exhibited in another study: Kefi *et al.* (2011) showed that soil erosion indirectly affects the fertility of soils by removing nutrients like Nitrogen and Phosphorus through transport process. Zalidis *et al.* (2002) showed interactions existing between soil erosion, organic matter decline and soil fertility loss. He supported that loss of organic matter affects the penetration of plant root, and thus decreases the moisture and permeability of the soil. Lynden and Oldeman (1997) also sided with such point of view. Moreover, they reported from different case studies (Sri Lanka, Bangladesh, Pakistan, and Thailand) that soil fertility decline resulted from soil chemical erosion in 70 percent of cases. According to Abahussain *et al.* (2002), soil removal and fertility loss are both indirect consequences of soil erosion through improper management policies.

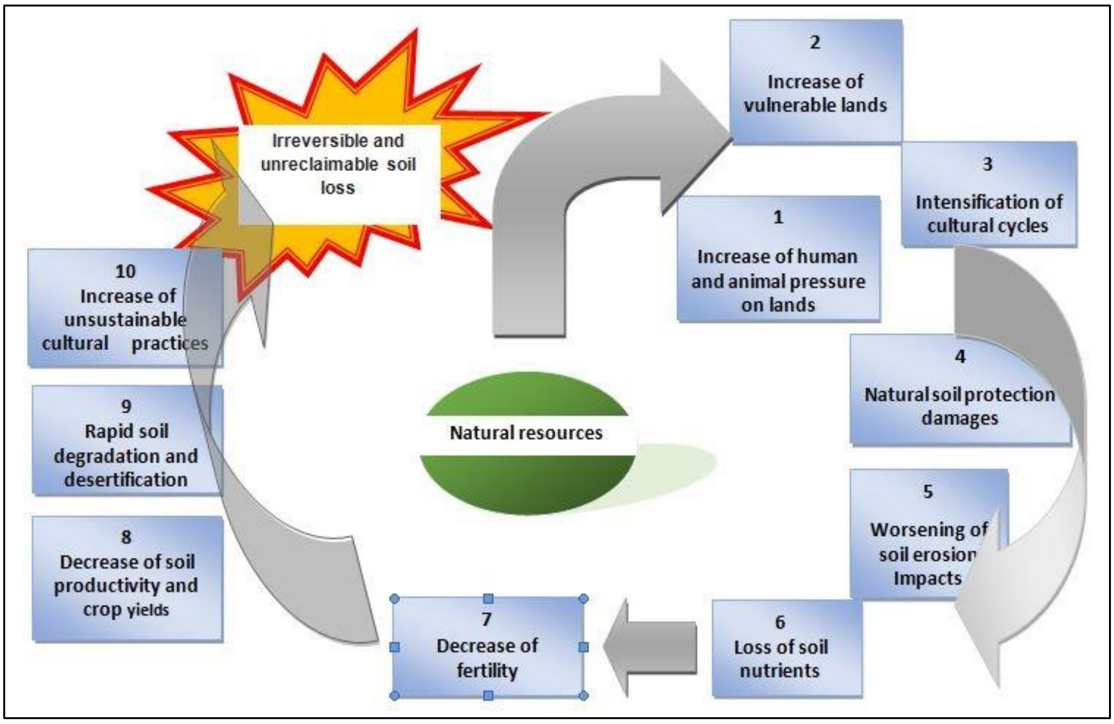

Figure 0.2: Soil degradation cycle (Source: UNEP, 2000)

2.5.2 Threats to food security

It is generally recognized that soil erosion has a major impact on fertility and productivity of soils. Many studies argued on interactions existing between rainfall-induced erosion and soil fertility decline. UNEP (2000) schematically described how soil erosion affects soil fertility which in turn results in a loss of productivity (figure 2.2). In this report, it was estimated that losses of N and P due to erosion process were three times higher than the total amount of fertilizer applied at growth stage. Yet decline of those nutrients play an important part in decreased soil fertility. As consequence, crop yields are significantly decreased. Another negative effect of soil erosion in long term is an irreversible degradation state of soils which in turn will constraint farmers to abandon their lands. Bronwyn *et al.* (2015) assessed impacts on land scarcity on food production. It was found that arable land availability will be outpaced by combined effect of rapid world population and global food demand increase. According to Foley *et al*. (2017), available crop lands will dramatically shrink due to rapid population growth never experienced before. Other scholars emphasized the incidence of soil erosion and land degradation on food scarcity. Lambin *et al.* (2013) point out that soil erosion as a result of climate change will affect potential croplands in dry lands. Gomiero (2016) supports that farmers are forced to abandon erosion-affected lands to use new lands that are in most cases, not productive unless heavy investment efforts are made to make those lands suitable for agriculture.

2.5.3 Water resources and biodiversity

Impacts of soil erosion on water resources are perceptible on both quality and quantity. As discussed earlier, nutrients of soil are removed and carried by erosion. Yet it was found that depositions of high nutrient concentration in water (especially N, P and K) can adversely affect the functioning of water ecosystems. (FAO and ITPS, 2015) reported that fertilizer increase as an indirect effect of soil erosion can result in pollution of local or regional waterways. Pimentel *et al.* (1995) suggest that eutrophication is one of the major offsite effects of heavy sedimentation in waterways. According to Zalidis *et al*. (2002), intensive use of fertilizers can destroy retaining pollutant properties of the soil, which will allow transport of those pollutants in water courses. It was also found that saturation of soil by high fertilizer inputs allows infiltration of high concentration of nitrogen and phosphorus in groundwater (*ibid*). As regards biodiversity threats, Scroll and For (2000) found that heavy sedimentation and increased turbidity lead to decline in zooplankton population, herbivorous insects and fishes as well as reduction in biomass diversity. Carpenter *et al*. (2017) made a contribution in assessment of indirect impacts of soil erosion on biodiversity. They found that enrichment of water by high concentration of nitrogen and phosphorus can increase algae and aquatic biomass which in turn leads to oxygen depletion and decline of aquatic animals (Carpenter *et al*., 2017; Zalidis *et al.*, 2002).

2.5.4 Desertification

There is very close interaction between erosion and desertification. Desertification is simply defined as a state of land degradation in dry lands (Kadomura, 2001; *Abahussain et al*., 2002). It refers to a decline or destruction of natural functions of soils and dramatic degradation of ecosystems (Kadomura, Hiroshi (Department of Environment Systems, Faculty of Geo-Environmental Science, Rissho University, 2001). It is estimated that desertification affects 70% of all dry lands and one-quarter of the total world land area of the world (Sivakumar, 2015). In fact, while a certain group of researchers support that desertification is a result of a permanent and recurring erosion process, it is all the same supported by another school of thoughts of scientists that erosion can as well be considered as a cause of desertification. For instance, Lal (2001) found that soil erosion in arid and semi-arid areas is mostly caused by desertification. This point of view is strongly refuted by other researchers. For instance, FAO and ITPS support that soil erosion is one aspect deriving from desertification which entails many other aspects (FAO and ITPS, 2015). Abahussain *et al.*, (2002) compiled causes and consequences of desertification occurring in Arab regions as a result of wind and water erosion. Causes include rapid population growth, high immigration rate, increased evaporation rate coupled with global warming, overgrazing and intensified agriculture (Abahussain *et al*., 2002). It is estimated that wind and water erosions respectively affect 161.3 million ha and 43.6 million ha of total area of the Arab region (*ibid)*. Besides Abahussain *et al.* (2002) discussed on consequences of desertification: Decrease of fresh water availability is one of the serious consequences of desertification in Arab regions.

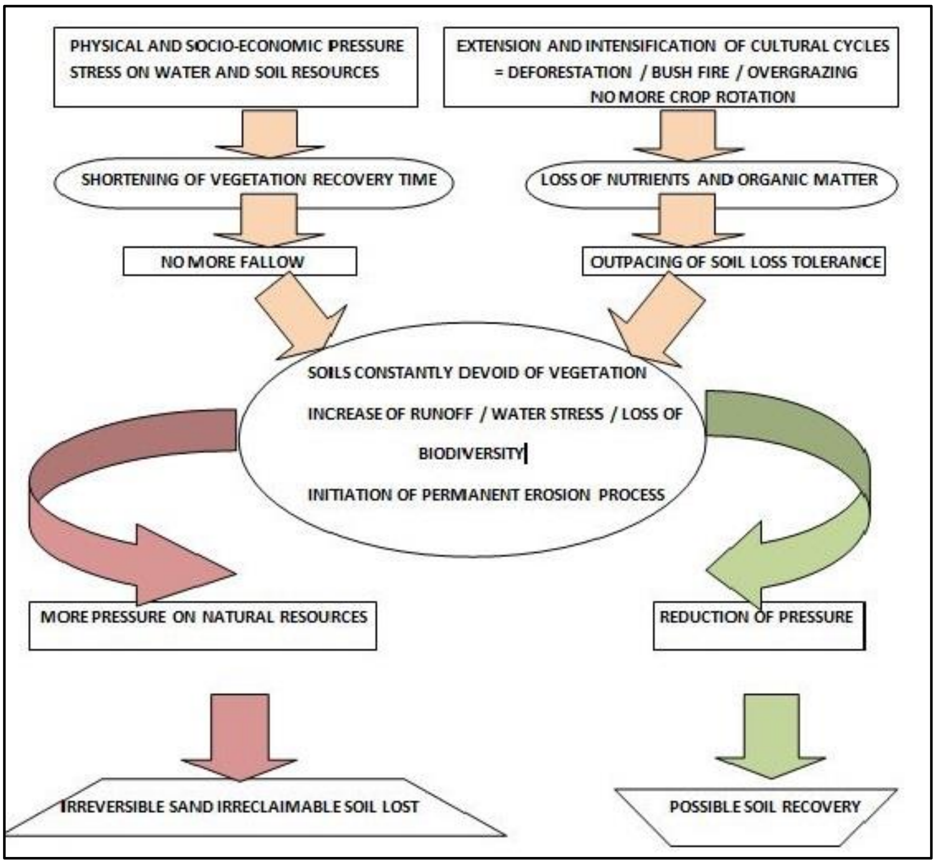

Figure 0.3: Mechanisms of desertification (Source: PAP/RAC, 1997)

Figure 2.3 shows a basic sequence of phases that can lead to desertification. Erosion evolving process towards desertification is influenced by numerous factors and processes that start with overuse of natural resources. When soil erosion intensifies and becomes recurrent, it should be considered as a sign and indicator of desertification risk. Studies have shown that such a process is ongoing in the Mediterranean region (UNEP/MAP/PAP, 2000). As a result of permanent and excessive stress on natural resources, soil degradation can evolve from erosion to an intensification trend of a reversible desertification state which can progressively become irreversible. Considering the extreme vulnerability of the Mediterranean biome characterized by a severe summer due to long periods of water stress, hydrological processes are deeply compromised by low vegetation cover and accidental topography. In such precarious context, additional stress on natural resources by droughts, bush fires, overgrazing and deforestation can adversely lead to an irreversible state of soil degradation and desertification. For instance, whenever there is a severe lack of water, there will always be intensification of socioeconomic activities associated with intensified forest fire and increase of pressure around water points by human and cattle. Unless regenerative actions are taken as attempts to recover land removal, irreversible desertification with irreclaimable soil loss exceeding any soil loss tolerance takes place. Another cause of desertification can be linked to loss of soil productivity and fertility. As consequence, extensive pollution as a result of excessive use of fertilizers, herbicides and pesticides can directly lead to a significant loss of vegetation cover and destruction of soil aggregates making the soil more prone to desertification.

2.5.5 Earth global warming

Intensified use of fertilisers as a result of nutrients losses erosion process can lead to increased nutrient inputs. Yet this increase of nutrient inputs especially nitrogen (N) was found to affect earth climate. FAO and ITPS (2015) investigated on different studies and concluded that an input of 1% of nitrogen gets back to the atmosphere in the form of nitrous oxide, which has a significant incidence on earth warning.

2.6 Geographic Information Systems (GIS)

Historically, knowledge of the land has been a primary concern for governments and for society as a whole. From the point of view of locating resources, analyzing the consequences of climate phenomena, forecasting crops, etc., men have always had to graphically represent their dominance over the world Events or information. Since the earliest times, classical cartography had responded to these social and economic needs, and especially to the military. In the light of the efforts needed to produce the cartographic document and the contributions of the computerized tool, the association between cartography and computing developed in the late 1960s with the appearance of software to aid Mapping. Indeed, with the combination of cartographic data and computing, resulting in a rapid and rapid development of hardware and software, the computer was given one of the most tedious tasks of the cartographer, Geographic information. Computer has become an efficient tool for cartographic production and spatial analysis. Geographic Information System (GIS) can be defined as a system developed to create, save, and process all kinds of geographic information (Pascual *et al*., 2012). GIS relates topographic information to environment or land use data in order to create maps (Steiniger & Hay, 2009). Different classification of GIS can be found in the literature but they are sometimes grouped in three classes according to their purposes they are used for. A. El Garouani (2016) classifies them into three groups: Web-based GIS (e.g. ArcWeb, MassGIS), Geobrowser (e.g. Google Earth)**,** Desktop GIS (e.g. ArcGIS). They range from high-powered analytical software to visual web applications. GIS puts together data of the same geometric and attribute nature (polygons, lines or points). Importance of GIS were recognized in numerous studies in assessing, monitoring and processing ecological data (Bhattarai & Dutta, 2007; Des *et al*., 2016; Kefi *et al.*, 2011; Steiniger & Hay, 2009). GIS was found to be useful tool in decision-making (Bayramin, Dengiz, Baskan, & Parlak, 2003; Bhattarai & Dutta, 2007).

2.6.1 Web-based GIS

Simply put, Web-based GIS are GIS using advanced Web-technologies (EL Garouani, 2016). It is an interaction between a server that may be any Web application and a user which can be a desktop or a mobile application (Pascual *et al.*, 2012). Those tools are recognized as very efficient storage, manipulation, visualisation, and spatial analyse data tools *(ibid)*. They have significantly contributed to a wider use of GIS applications. According to Dragiéevié (2004) Web-based GIS applications enable more dynamic and interactive maps between users and make data sharing easier (ibid). Moreover, they are user-friendly and particularly useful as they don’t require data download (Hardie, 1998). There are many Web-GIS available online: ArcWeb, MassGIS. However, their functionality is limited compared to software stored on your computer.

2.6.2 Geobrowser

The concept of geobrowser can be well understood with reference to Internet Explorer. A geobrowser is an Internet Explorer for geographic information. It therefore allows the combination of many types of geographic data from many different sources. Dugmore and Newton (2009) investigated the importance of such tools in processing and analyzing vector and attribute data. Although their drawbacks, geobrowser applications remain useful tools that can be used to better display and process spatial vector data (ibid).

2.6.3 Desktop GIS

It is defined as mapping software installed on a personal computer and allows representation, processing, and spatial analysis of geographic data (Steiniger & Bocher, 2009). Drawbacks of use of such software include their system complexity, difficult operations, and large storage requirements. However, they are highly appreciated by experts. Numerous soil assessment studies from different regions in the world including Mediterranean regions have used desktop GIS software (Nicholls. and Hoozemans, 1996; Lal, 2001; Abahussain *et al.*, 2002; Bayramin *et al.*, 2003; Kefi *et al.*, 2011; Des *et al.*, 2016; Raissouni *et al.*, 2016).

2.7 Models

Özhan (2002) supported that models enable users and policy makers to have a good understanding of scales and constitution of erosion factors which in turns contribute to efficient prediction of soil erosion as means to implement rational control of soil erosion. For Tiwari *et al.* (2000), models are defined as descriptors helping to understand physical mechanisms occurring in erosion processes. Attempts to model erosion processes by water developed 500 years ago (Renard, Foster, Weesies, McCool, & Yoder, 1997). Cook was the first to assume that soil erosion processes could be influenced by three major parameters : Rainfall erosivity, vegetation cover protection and soil erodibility (Morgan, 2005). This discovery allowed further research to come up with equations governing soil erosion processes. Zing proved that soil erosion depends on slope inclination and length (Morgan, 2005). The next year, another scholar called Smith (1941) found that soil erosion is strongly driven by agricultural practices that are on-going on the land (Renard *et al*., 1997). Further development of the Smith soil erosion equation were carried out by Browning and associates who elaborated a more developed equation by introducing factors that take into account soil erodibility and practices of management. In 1947, the equation widely known as the Musgrave equation was developed (Renard *et al*., 1997). It includes rainfall, soil protection cover, runoff and soil properties such as pedology and lithofacies. It is not before 1965 that Wischmeier, Smith and many other researchers proposed the equation known as Universal Soil Loss Equation (USLE), which combines six input parameters of soil erosion.

2.7.1 Physical-based models

They are used to evaluate soil erosion processes by combining and integrating factors influencing soil erosion (Morgan, 2005). The advantage of using physical-based models is that they offer the possibility of modelling soil erosion spatially and temporally (Bhattarai & Dutta, 2007). However, there is a major snag to their use. For the great majority of researchers in the area of soil erosion, physical-based models are found to be data intensive demanding models due to the fact they require a high number of parameters which are not necessarily from the same fields of research (Bhattarai & Dutta, 2007). As remarked Morgan (2005), the application of these models and their underlying factor relationships to different climatic and management conditions of other regions in the world is not always possible or appropriate. Physical-based models include:

a) Water Erosion Prediction Project (WEPP)

Water Erosion Prediction Project (WEPP) is a soil erosion model developed by USDA in 1985 using a steady state sediment continuity equation governing soil erosion processes. According to Brazier and Beven (2000), WEPP model uses four soil erosion influencing parameters that are include climate, slope, soil and management practices. For Yuksel *et al.* (2006), WEPP not only helps to predict amount of sediment yields but also can help to know the place and the moment from where and when they were produced. WEPP is very data demanding model that requires a large number of inputs. For instance, Brazier *et al.*(2000) found that WEPP model can require up to 50 input parameters, which can bias the results and lead to equifinality.

b) ANSWERS

Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) model is comprised of two models whose one evaluates hydrologic processes whereas the other assesses erosion (Beasley, 2016). This model is acknowledged to be a very flexible tool that can be applied in different scenarios (Bayramin *et al*., 2003; Lal, 2001). Research has shown that ANSWERS can model hydrologic processes on agricultural watersheds with large acceptance (Abdullah & Mahmut, 2006). The authors are confident that ANSWERS model can be applied to non-gauged watersheds for obtaining at least comparative results for various treatment or management strategies (Bhattarai & Dutta, 2007).

c) GUESS

GUESS (Griffith University Erosion Sedimentation System) is a mathematical model that simulates the processes of erosion and deposition along a hillside (Morgan, 2005). The model is designed as a guide to farmers, scientists and extension workers concerned with the evaluation and control of soil erosion by water. Soil erosion at any position on the slope and at any time during the storm is related to a sediment flux that depends on the hydrological conditions and the sediment concentration. The model differs from WEPP in separating the surface soil into two parts: that which is the original soil and possesses a certain degree of cohesion and that comprising recently detached material with no cohesion.

d) KINEROS

Kinematic Runoff and Erosion Model (KINEROS) is a distributed and physically-based model describing the processes of soil erosion in small watershed. According to Smith *et al.* (1994), KINEROS has been used more as a runoff assessment model than a soil erosion model. KINEROS uses conservation and momentum equations to describe soil erosion processes (Morgan, 2005). KINEROS separates raindrop process from transport process (*ibid*). It is widely applied in USA and UK and it entails boundary conditions which are not easy to be determined (Brazier *et al*., 2000).

2.7.2 Empirical models

a) Quantitative models

RUSLE

RUSLE model was developed by W. H. Wischmeier, D. D. Smith, and other scientists (Brazier *et al*., 2000; Renard *et al.*, 1997; *Renard et al*, 1991). Its equation is defined as follows: $E = R \times K \times LS \times C \times P$ where E is the mean annual soil loss, expressed in t/ha/an, R refers to rainfall erosivity factor, K is erodibility factor, L the length slope factor, S refers to slope steepness factor, C is the vegetation cover factor and P refers to erosion control practices factor. The erosion influencing factors in RUSLE are defined as follows:

- **Rainfall Erosivity factor:** It is defined as the product of the rain energy by the maximum of 30-minute duration rainfall intensity. It can also be considered as the average annual rainfall erosion index.
- **Erodibility factor (K):** The erodibility factor (K) expresses the vulnerability and the susceptibility of a given soil to erosion. K is estimated from a reference standard plot evaluated by taking into consideration texture, organic matter content, soil structure and permeability without taking into account the vegetation cover and Cultural practices.
- **Slope length factor (L):** It can be integrated with slope steepness factor (S) to compose one single LS factor defining the fraction of soil loss under slope steepness and slope length

conditions to soil loss for a unit LS factor (Morgan, 2005). LS factor is determined either by using monographs or through the following equation:

$LS = \left(\frac{I}{22.13}\right)^{0.5}(0.065 + (0.045 \times 12) + 0.0065 \times 12^2))$ where *x* (m*)* is the slope length, *s* (%) is the slope gradient and *n* depends on lope steepness.

- **Vegetation cover:** The vegetation cover factor is a simple relationship between erosion on bare soil and erosion observed under a protection system. The same factor C combines both the vegetation cover, its level of protection and the associated cultivation techniques. This factor varies from 1 on bare soil to 1/1000 under forest, 1/100 under grassland and cover crops, 1 to 9/10 under cultivation conditions.
- **Erosion control practices factor (P):** This factor evaluates the effects of practices to change soil profile, slope or direction of surface runoff flow and thus reduce erosion. According to Renard *et al.* (1997), RUSLE model is applicable as long as data of erosion equation governing factors are available. However, although widely applied to simulate soil loss, suitability of application of both USLE and RUSLE models for evaluating soil erosion in several other regions has not been discussed enough (Renschler *et al.*, 1999). The RUSLE soil erosion assessment model is an empirical model for quantifying soil erosion that incorporates the USLE terms by correcting some inaccuracies. RUSLE normally applies to landforms of topographic profiles and allows for erosion at the farmland scale: However, it is possible to extrapolate to map erosion on larger areas such as entire agricultural regions (Spanner *et al.*, 1982 cited in Bonn, 1998). The method consists in applying each factor of the RUSLE equation to georeferenced spatial data. The multiplication of all the layers of information obtained gives an erosive risk map for each cell with an erosion value expressed in t / ha / year. However, RUSLE has several disadvantages that Roose (1994) has summarized as follows: It applies only to area-scale erosion at the watershed or field scale, and in no case to linear erosion, Mass erosion. It applies only to area-scale erosion at the watershed or field scale, and in no case to linear erosion, mass erosion. The kinetic energy intensity relationships of rainfall used in the RUSLE model are a priori valid only in the American plain. They are not valid in any case in mountains where the types of rain are different. This prediction equation obviously neglects the possible interactions between factors. This model applies only to average data over several years and my step to the rainfall scale. RUSLE is acknowledged to be an good

model to simulate and quantify annual soil loss caused by raindrop splash and runoff processes occurring under specified conditions of land management, cultural practices and under physical conditions such as slope (Renard *et al*., 1997). Solving functions of erosion governing equations in RUSLE are more developed than those in USLE, and moreover computer programmes make its use easier (Renard *et al.*, 1997).

b) Qualitative models

Qualitative methodology aims at assigning weights to different surfaces within a watershed according to their erosion state. Qualitative model is very useful for erosion mapping in large areas and helps to plan appropriate erosion control measures (Kefi *et al.*, 2011). They consist in prioritizing the surface of a given catchment into units based on weights according erosion vulnerability. Qualitative models give a spatial representation of soil erosion risks. As Kefi *et al*. (2011) remarked, qualitative models are very useful for spatial distribution of soil erosion occurring in large areas (Kefi *et al*., 2011). Moreover, they provide the opportunity of identifying the different forms of erosion (ibid).

i) ICONA

ICONA is a model developed by the General Directorate for the Conservation of Nature (Kefi *et al.*, 2011). It is a qualitative approach widely applied in Europe and Mediterranean countries to evaluate soil erosion risk in large areas (Bayramin *et al*., 2003; PAP-RAC, 1997). ICONA model enables a rapid evaluation of rainfall-induced erosion risk in a given watershed (ibid). Data required to run ICONA include land use, vegetation cover and slope and soil lithofacies (Kefi *et al.*, 2011); (Bayramin *et al.*, 2003). The final output of ICONA model is a synthesized map obtained by overlapping soil protection map obtained by combining land use layer with vegetation cover layer, and erodibility map obtained by overlapping together slope layer and lithofacies layer, which provides information on rock types and their cohesiveness (Bayramin *et al.*, 2003). This final map gives a spatial distribution of erosion risk in the watershed. Modelling soil erosion risk using ICONA consists of combining soil protection map which is obtained from overlaying vegetation cover and land use map with the soil erodibility map resulting from slope and lithofacies layers (Kefi *et al.*, 2011). The use of ICONA model is limited by a major drawback: it does not integrate climatic considerations, which tends to taint its accuracy (Bayramin *et al*., 2003).

ii) PAP/RAC

PAP/RAC is a qualitative method that aims at identifying and classifying watershed surfaces in separate units according to their erosion vulnerability (Siham, Abderrahi, Midaoui, Faiza, & Benabdelhadi, 2016). It enables identification of the most fragile areas prone to erosion (*ibid*). In an attempt of assessing and qualitatively mapping soil erosion in Aoudour watershed which is 1000 km^2, that is to say, 30 times bigger than Boufekrane watershed, and presenting very close lithofacies similarities with Boufekrane region which is mainly dominated with friable lands, Siham *et al*. (2016) found that PAP/RAC is adapted and suitable to assess erosion in small watersheds because it best integrated the smallest land parcels of Aoudour watershed. Furthermore it is adapted with the local climatic conditions (Siham *et al*., 2016). PAP/RAC method is recognized as a good decision-making tool for soil erosion control and management (PAP-RAC, 1997). It enables a mapping of high risk areas prone to erosion, which constitutes a prerequisite to an efficient decision-making and effective integrated management of costal Mediterranean areas (PAP-RAC, 1997). Moreover, PAP/RAC model is accepted to be cost-effective and less time consuming given the flexibility of its guidelines. Demonstration exercises on the applicability of soil erosion assessment and measurement PAP/RAC methodology were carried out in three case studies representing three different types of watersheds of the Mediterranean region for: Vallcebre (Spain), Essen (Turkey) and Ermel watershed (Tunisia). The national reports of coastal Mediterranean countries confirmed the flexibility and adaptability of the PAP/RAC soil erosion assessment methodology (Albania Coordinating Board, 2002; Özhan, 2002; UNEP/MAP/PAP, 2005). This methodology is innovative because it allows to present on a single integrated map both erosive states and the dynamics of erosion. Compared to traditional mapping systems, it has considerable advantages in controlling erosion processes and managing Mediterranean coastal areas.

Chapter 3

MATERIALS AND METHODS

2.8 Study Area

The area of study is within Boufekrane, which is in turn part of a greater catchment, Fez watershed also known as Oued Ljaouahir. Boufekrane covers an area of 52 km^2 and a length of 29 km. Boufekrane watershed has it source at El. It lies at the eastern boundary of the Oued Fez watershed, but also of the plateau of Saïs. This catchment has a long shape very with a Gravelius compactness index of 2.44, in the form of a valley more or less enclosed. The regime of Boufekrane is mainly characterized by a typically Mediterranean climate with a rainfall regime. During the summer period, Boufekrane watershed witnesses a slight depletion due to drying up of its affluent rivers. Most of the watershed is characterized by dominance of friable rocks (marls), allowing different forms of erosion to develop. The watershed of study has a perimeter estimated to 3.28243 km. Agriculture is one of the most important sectors of the region economy. Boufekrane watershed is subdivided into two parts: The plain of Fez where our study basin belongs and the plateau of Meknes. These two parts are separated by the accident of Ain Taoujdat which crosses the region in scarf NW-SE. This study concerns the Oued Boufekrane basin which is part of the plain of Saiz Fez. The Boufekrane watershed originates from the Bhalil region, and follows a flow direction NW-SE. The area is 32.97 km2. During his path, he receives water from several sources. It is bounded in the north by pre-riferous wrinkles in the south by the tabular atlasic causses (Causse de Sefrou), to the east by the valley of the Sebou watershed, and to the west by the plateau of Meknes. The basin is classically subdivided into two parts: The Plateau of Meknes and the plain of Fez, to which the study area belongs. These two MAIN parts are separated by Taoujdat geological fault which crosses the region in escape NW-SE.

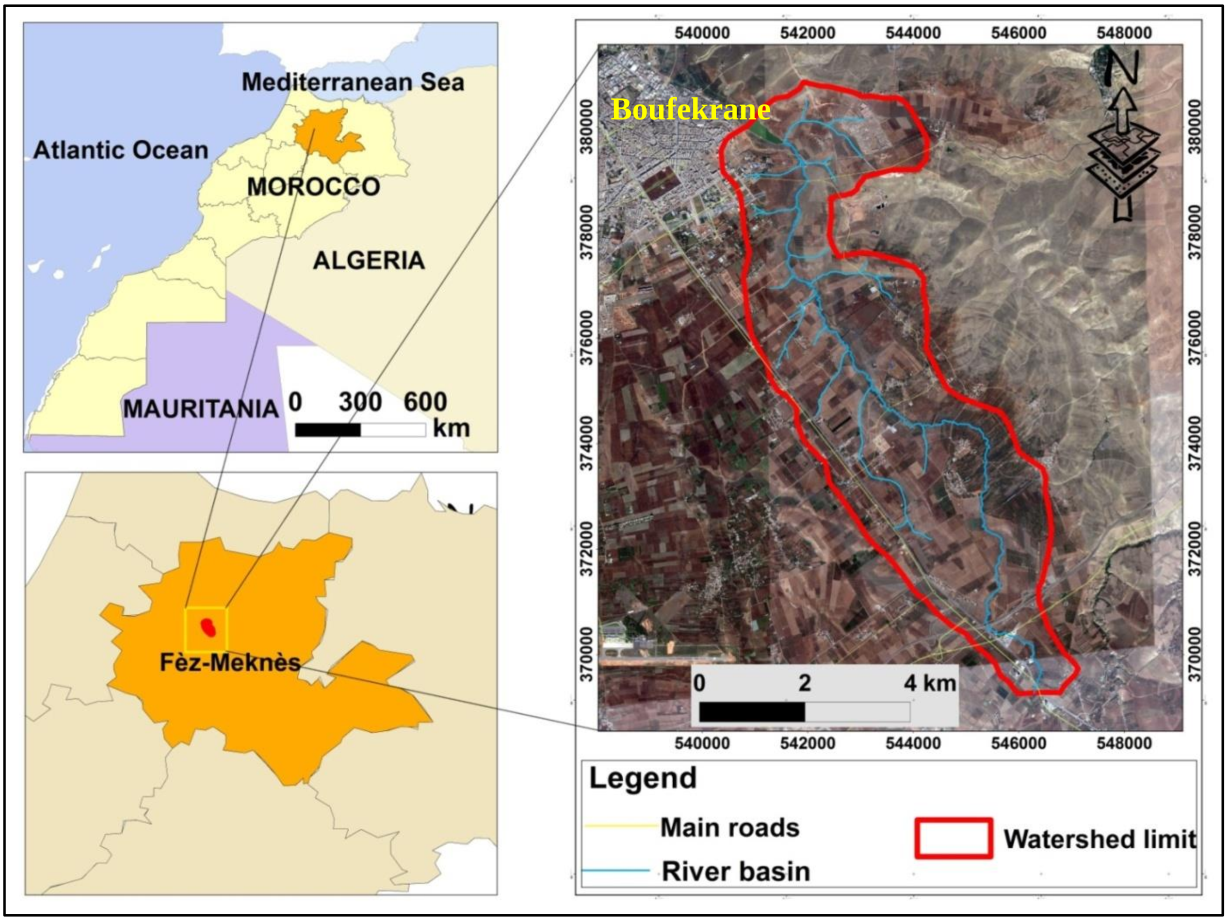

Figure 0.1: Location of Boufekrane watershed in Morocco and Fez-Meknes region

2.8.1 Administrative structure

Boufekrane is part of Fes-Meknes region covering an area of 0.075 km² and representing 5.7% of the total national territory. Administrative boundaries of Fez-Meknes are defined as follows:

- In the north, the region of Tangier-Tetouan-Al Hoceima;

- In the West, the region of Rabat-Salé-Kénitra;

- In the south-west, the region of Beni Mellal-Khénifra;

- In the East, the region of the Oriental;

- In the South, the region of Drâa-Tafilalet.

The Region of Fes-Meknes comprises two counties: the county of Fez and that of Meknes. It also has seven provinces: Boulemane, El Hajeb, Ifrane, Moulay Yaâcoub, Sefrou, Taounate and Taza. Fez-Meknes is composed of 194 communes including 33 municipalities and 161 municipalities Rural.

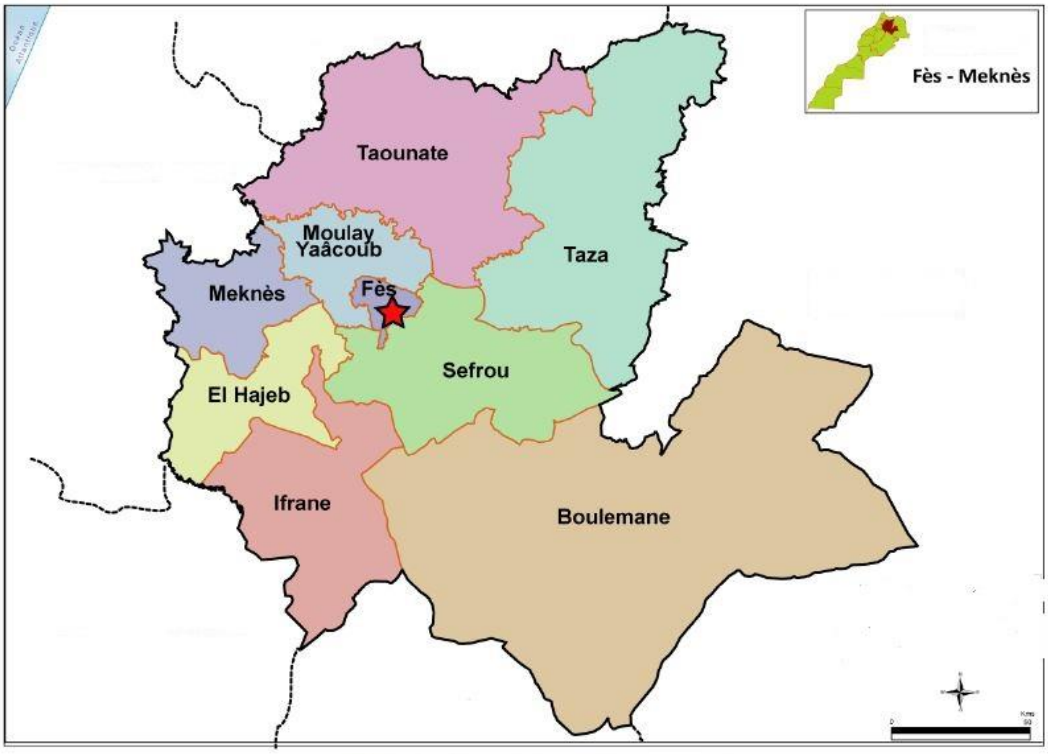

Figure 0.2: Administrative division of Morocco

2.8.2 Socio-economic background

a) Population

According to the General Population Census and of the Habitat of 2014, the Region of Fes-Meknes accounts for 4,236,892 inhabitants, against 3,873,207 in 2004, 60.52% are urban. The distribution of the population by province and prefecture shows the dominance of the dipole Fez-Meknes, which contains 47% of the population of region, followed by the province of Taounate which comprises 15% of the population.

b) Population density and growth rate

Fes-Meknes region, which covers only 5.6% of the Kingdom's area, is home to 13% of the population in 2014. This is reflected in the high level of regional density of about 105.7 inhabitants per square kilometre, as against about 47.6 at national level. At communal level, the density varies from 2% (30 communes have a density lower than 30 inhabitants per Km^2) and 55,600 inhabitants / km^2 at the level of the Prefecture of Fez. According to 2014 general population and habitat census, population of Fez-Meknes was estimated to

4,236,892 which accounts for almost 13% of Morocco total population. The population growth rate of Fez-Meknes is estimated to 1.61%.

c) Urbanization

According to the 2016 Regional Statistical Yearbook of Fez-Meknes, the urban population of Fez-Meknes region is estimated to 2,564,220 and represents 60.5% of its total population. The urban population has increased by 1.52% per year on average two last censuses against a decline of the rural population of -0.56%. It is expected that this trend would continue over the next few years. As a result, the rate of urbanization in Fes-Meknes region reached 60.52% in 2014 against 62% in 2004. More than two thirds of the urban population of the region is concentrated in the two counties of Fez and Meknes where live 71% of the region total urban population with an urbanization rate respectively estimated to 0.98% and 0.82% (2014 census). Provinces of Fez-Meknes have different urbanization rates ranging from 0.14% (province of Moulay Yaâcoub) to 0.4% (province of Taza). Urbanization in Fez-Meknes is characterized by important economic activities and population concentrated in Fez and Meknes. Fez and Meknes are considered as the most important cities of the region.

d) Economic activities

Fez is recognized as the regional metropolis where economic assets and infrastructures play a key role in the economic development of the region. Fez is well-located strategically with a position on a road crossing connecting two axes: The Rif and the Middle Atlas on one hand and the Atlantic Ocean in the East. This strengthens its economic, political and social role. Meknes as the second regional metropolis has been designated as a World heritage by UNESCO. Aged for at least ten years, Meknes has also a very geostrategic position. It provides significant economic assets due to its bulky water resources attracting human settlement and development of communication networks. In addition, the rural nature of Fez-Meknes region as well as the large proportion of working force makes agriculture the most important sector of the local economy. Agriculture remains the essential activity for the population of the plain of Sais. It is developed mainly outside the urban areas of Fez in the plain of Sais, which comprises nine rural communes: Sbaa, Rouadi, M'haya, Ain Chkef, Ain Bida, Ouled Tayeb, Laqsir, Ain Taoujdat, Ain Cheggag, and Kandar Sidi Khiar. Fez-Meknes agriculture is mainly based on production of cereals, vegetables and fruit trees (olive, fig, and almond). The Utilised Agricultural Area (UAA) is estimated to 1.335.639 hectares accounting for 15% of the total agricultural area (Direction Générale des Collectivités

Locales, 2015). The total area of lands equipped with an irrigation scheme is estimated to 1,251, 456 hectares which accounts for 9% of the total agricultural lands of the region. The region of Fez-Meknes has a huge potential of arable lands estimated to 1.4 million of hectares. In all, Fez-Meknes region has about 1.7 million of people living in rural areas and intensively practicing farming activities including agriculture, livestock production (cattle, sheep and goat) and grazing.

2.8.3 Pedological background

From a general point of view, Boufekrane soils are closely intertwined with one another forming a mosaic. Two main factors are responsible for the diversity of soils and their spatial distribution in the watershed. Those factors are the bedrock and the topography. In the plain of Saiss, the rocks are diversified: conglomerates, red clay, limestone, sand and sandstone, marls and basalts. Most of those rocks contain an important proportion of carbonates. Hard calcareous soils (calcareous and sandstone, etc.) are formed first on calcimagnetic soils which can become isohumic, even fersialitic soils. On marl rocks (rich in swelling clays), soils quickly acquire the characteristics of vertisols. The basaltic rocks give rise to red soil with an anatomical tendency. The topography modifies locally the drainage conditions. Indeed, the soluble elements released by the alteration upstream of the slopes concentrate downstream: The upper part of slope, characterized by a deficiency of silica and bases, are the kaolinite formation, whereas the confined areas of the base of the slopes are characterized by a massive formation of swelling clays. In upstream, lateral and vertical compression stresses are exerted on soils, whereas in downstream the soils are enriched. The soil-absorbing complex of sloping areas tends to desaturate into cations and thus to the vertical and lateral leaching of the clays. In the poorly drained areas (bottom slopes), the soils are saturated, the clays are not leached and the profile homogeneous. Besides those two main factors (bedrock nature and topography), one can evoke the action of water table and impacts of human activities. Level of aquifers sometimes reaches the ground and tends to temporary or permanent flooding, which can lead to a hydromorphic condition. Similarly, human by his various activities (tillage operations, inputs of chemicals, cultural practices, etc...) adversely affects characteristics of the soils of the plain of Saïs. Other physical factors that can influence the pedology of soils include atmospheric gases, plants and organic matter content. Boufekrane pedological map (figure 3.3) shows that the study area is composed of five soil classes. The most representative soils in Boufekrane watershed are classified as follows:

a) Calcimagnesic soils (Figure 3.3)

The nature and composition of calcareous materials combined with topography effects are ecological factors that lead to formation of calcimagnesic soils. They are the most represented types of soil and cover an area of 21.82 km^2 which accounts for 66.12% of the total watershed area. Depending on local conditions, they are found to influence consolidation of soil with a relative efficiency depending on presence of limestone in intimate contact with organic matter.

Figure 0.3: Calcimagnesic soils (El Aroussi, 2014)

b) Vertisols

Vertisols illustrated in photo 3-4 are concentrated in the northern part of Boufekrane where slopes are mainly steeper (Assia Ouazzani, 2008). This factor contributes to erosion process increase. Vertisols cover an area of 6.41 km^2 of Boufekrane watershed, which accounts for 19.42% of the total area. Vertisols are always located at the bottom of slopes.

Figure 0.4: Vertisols (El Aroussi, 2014)

c) Isohumic soils

Isohumic soils (photo 3-5) cover an area of 3.49 km^2 which represents 10.58% of the total watershed area. They predominately develop on clay alluviums. Their evolution is mainly influenced by general bioclimatic factors such as climate and vegetation. They are characterized, on the one hand by maturation of organic matter, and on the other hand by formation of swelling clays. This change is strongly dependant of climate, soil moisture contents and abundance of alkaline cations such as calcium and magnesium. Isohumic soils are usually well structured and well aerated.

Figure 0.5: Isohumic soils (Omar El Aroussi, 2014)

d) Poorly developed soils

Poorly developed soils (photo 3-6) develop in moderate to steep slopes (3%-12%) of high reliefs and on soft materials that are very vulnerable to erosion by water. They account for 2% of the total watershed area. Most of these soils have a tendency towards calcimagnesic soils. There is often a darkening of the superficial horizon due to the maintenance of organic matter in the surface horizon by limestone.

Figure 0.6: Poorly developed soils (Omar EL AROUSSI, 2014)

e) Dimanganese trioxide

They are very poorly represented in watershed, and they occupy only 1.76% of the total watershed area. They develop in hot areas, with a medium very rich in iron oxides.

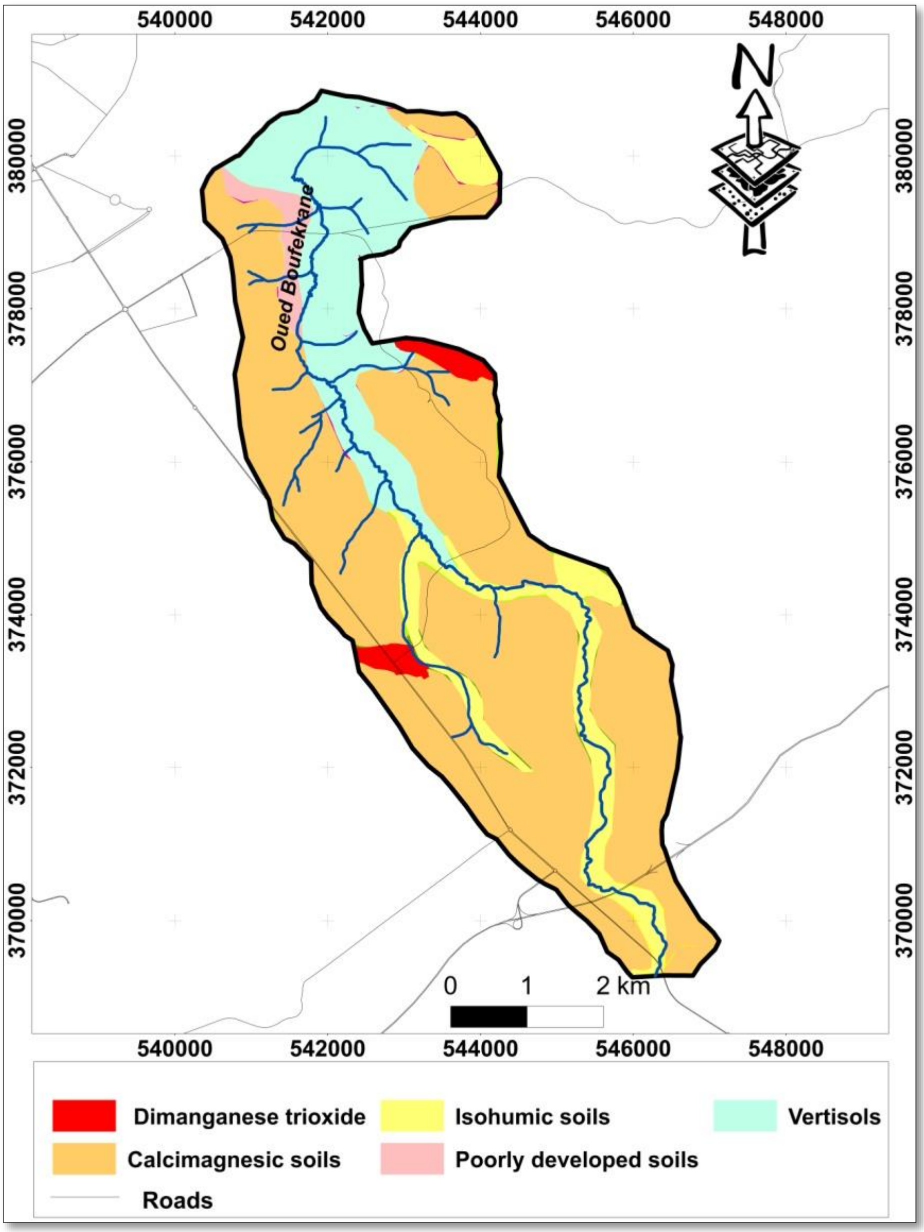

Figure 0.7: Pedological map of Boufekrane

2.8.4 Geological characteristics of Boufekrane

The lithology of Boufekrane watershed is mainly dominated by two geological formations: the marls of the Miocene and the lacustrine deposits of Quaternary as shown in figure 3.8. The Miocene marls, which constitute 12.7% of the surface of the basin, are extremely unstable, plastic and vulnerable to slippage. The Quaternary is the most dominant formation in this basin, occupying almost 88% of its surface. It is characterized by diversified facies: compact composed of calcareous conglomerates and plastic formed of clays and clay loams.

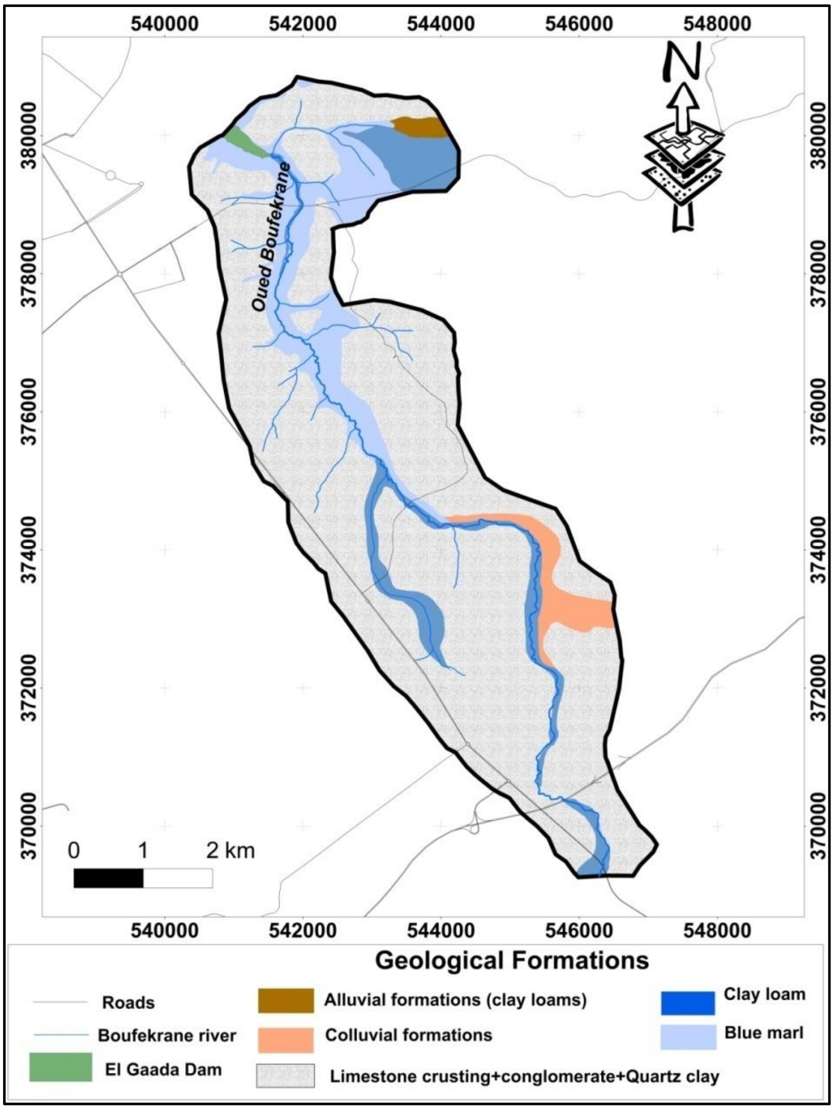

Figure 0.8: Geological map of Boufekrane

2.8.5 Climatic background

a) Rainfall

Given that rainfall is one of the most important erosion influencing factors, it is momentous to study annual and monthly precipitations of Fez-Meknes region in order to better understand the role of rainfall in erosion processes in Boufekrane.

i) Mean annual rainfall

Rainfall records have been made over the period 1984-2014 which corresponds to 31-year period. The average interannual precipitation obtained for this period is 421.7 mm. Globally, one can remark that Saiz-Fez region is relatively well drained since average rainfall reach 500 mm. Figure 3.9 showing the mean annual precipitations, indicates that 2009-2010 is the wettest year period with an interannual precipitation estimated to 838.0 mm whereas 1992-1993 is recognized as the driest year with an interannual precipitation estimated to 181 mm. November with a rainfall of 64.6 mm is the wettest month while the month of July is the driest month with a precipitation of 0.7 mm.

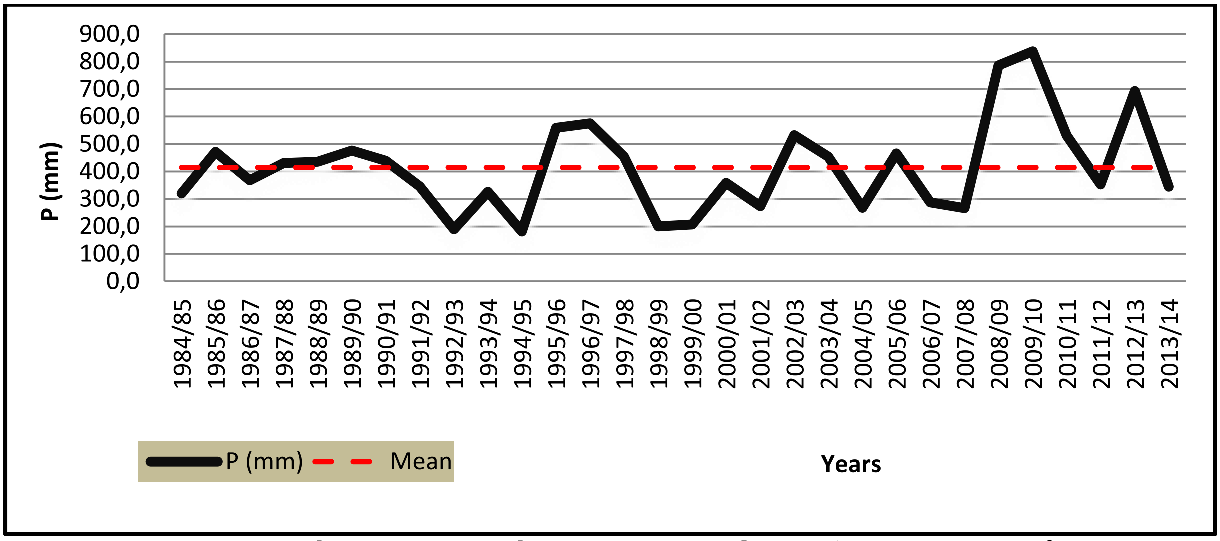

Figure 0.9: Mean annual precipitations between 1983 and 2013 (Gauge station of Fez-Sais, 2016)

ii) Mean monthly rainfall

From table 3.1, mean monthly precipitation was calculated and was estimated to 35.14 mm. November is found to be the wettest month with a mean precipitation estimated to 66.1 mm whereas August is the driest month with a mean monthly precipitation estimated to 1.6 mm (figure 3.10).

Table 0.1: Mean monthly precipitation (Source: Gauge station of Fez-Sais, 2007)

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	Total
P(mm)	62.2	49.2	50.0	45.1	27.0	8.0	0.7	1.6	13.4	38.1	66.1	60.4	**421.7**

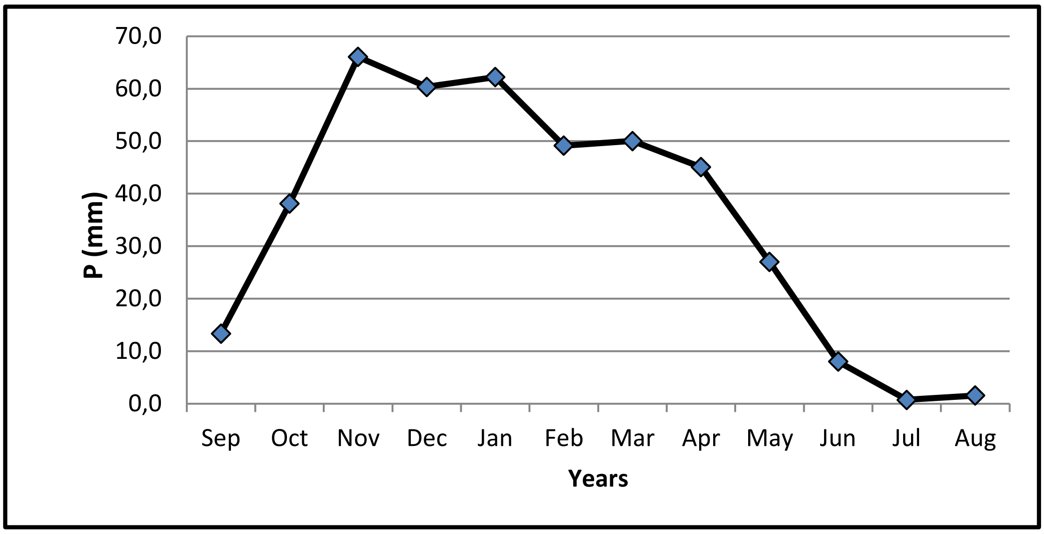

Figure 0.10: Mean monthly precipitation between 1983 and 2013

b) Temperature

i) Interannual temperatures

Mean annual temperature data presented in figure 3.11 was obtained from DRH Fez gauge station. The mean annual temperature over the period 1983-2013 is estimated to 17.3°C. The average annual maximum temperature is 18.75 °C recorded in 2009, while the minimum annual average temperature is estimated to 16.23 °C obtained in 1991.

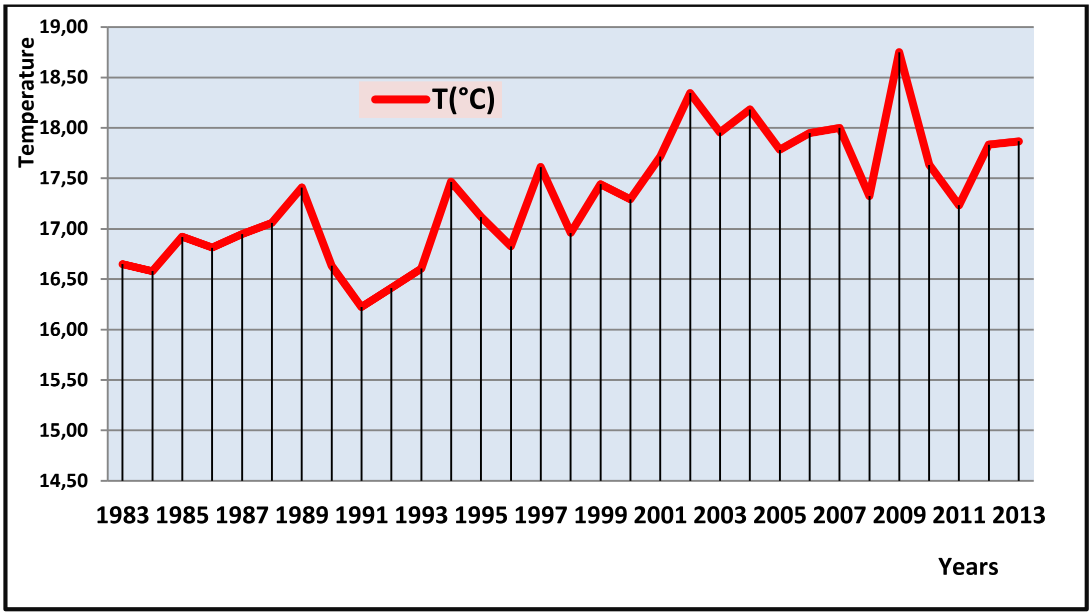

Figure 0.11: Mean annual temperatures between 1983 and 2013 – DRH Fez Station

ii) Mean monthly temperature

Table 3.2 shows the mean monthly temperatures obtained over the period 1983-2013. It shows that August and July are the hottest months whereas January is the coolest month with 9.6°C.

Table 0.2: Mean monthly temperatures (1983-2013) – DRH Fez Station

Month	Sep	Oct.	Nov.	Déc.	Jan	Feb	Mar	Apr.	May	June	July	Aug
T (°C)	22.9	18.9	14.0	10.9	9.6	10.8	13.0	14.7	18.2	22.4	26.2	26.3
ETP (mm)	136	120.7	100.5	86.6	80.1	85.9	96.4	103.9	118	134.2	147.5	147.9

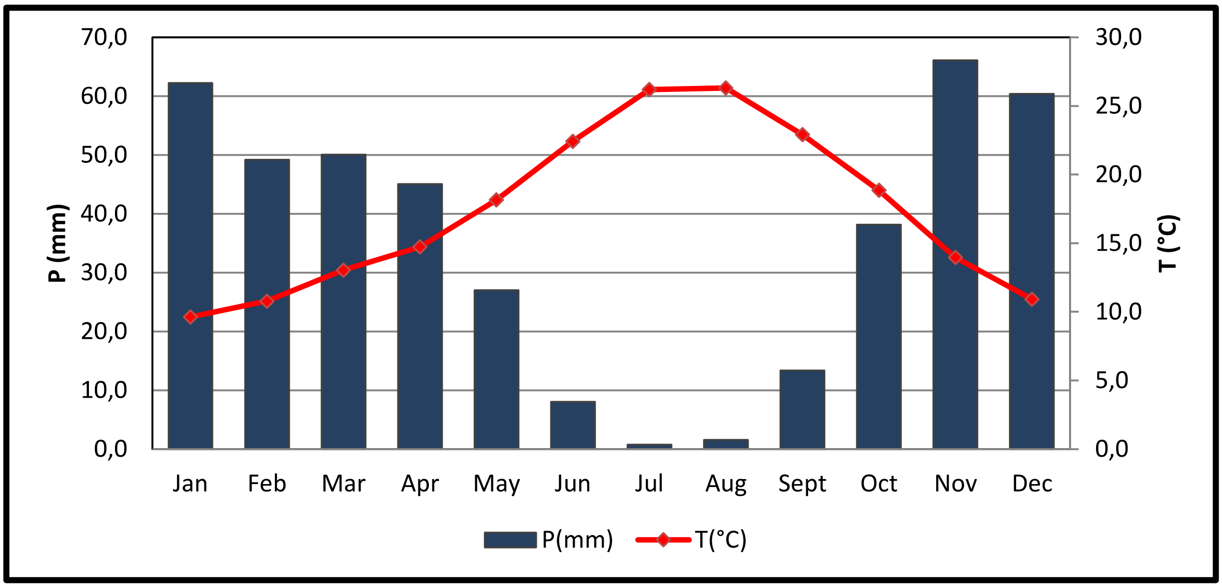

Figure 0.12: Rainfall/temperature diagram of Boufekrane watershed

c) Climate aridity

Observations of Morocco climate helped to understand season distribution over the year: Winter includes December, January and February (with a mean monthly rainfall estimated to 40.7 mm), Spring include March, April and May (with a mean monthly rainfall estimated to 32.0 mm), Summer include June, July and August (with a mean monthly rainfall estimated to 2.3 mm, and Autumn include September, October and November (with mean monthly rainfall estimated to 27.5 mm). Aridity of Boufekrane watershed was determined by using Bagnoouls and Gaussen diagram, which consists of determining dry periods over the year. Dry months are those of which rainfalls are less than the double of the average temperature recorded in the considered months. Analysis of rainfall/temperature diagram in figure 3.12 shows that May, June, July, August and September are months of dry season. Moreover, aridity of a given region can be determined by using indexes which are quantitative metrics of water shortage. Martonne's aridity index, is one of the most widely used equations. It is defined as follows:

$$I = \frac{P}{T+10} \qquad \text{eq.(i)}$$

- P (mm) is the annual rainfall
- T (°C) is the annual average temperature.

According to aridity index values, it is possible to classify a climate as follows:

For $I < 5$, arid or desert region
For $5 < I < 10$, arid or steppe region
For $10 < I < 20$, semi-arid region
For $I > 20$, sub-humid to humid region

In this study, the annual rainfall and the annual temperature were determined based on Fez gauge station data. It was found that for P = 421.7 mm and T = 18°C, I = 15.06. Boufekrane is therefore located in a semi-arid region.

2.8.6 Evapotranspiration

It encompasses two physical phenomena: Evaporation and transpiration. It reflects total losses of water through plant transpiration and soil evaporation. One can distinguish two types of evapotranspiration: Potential evapotranspiration (ETP) and actual evapotranspiration (ETR).

d) Potential evapotranspiration

Potential evapotranspiration is defined as the amount of water that could be evaporated and transpired if there was enough water to be compensated for maximum water losses. In other words, this parameter reflects the climatic demand and represents the evapotranspired water slice under excess feeding conditions. ETP is closely related to temperature. To approach the ETP, many empirical methods introducing this parameter have been proposed, the most widely used of which is that of Thornthwaite. Different equations are used to assess potential evapotranspiration but the most widely used equation is that of Thornthwaite expressed as follows:

$ETP = 16 \times (\frac{10T}{I})^{a}$ eq.(ii), where I is the annual thermal index obtained by summing the 12 monthly indexes (i).

$i = (\frac{T}{5})^{1.514}$ eq. (iii) and

$a = 0.94239 + 1.79 \times 10^{-5} \times I + I^{2} + 675 \times 10^{-9} \times I^{3}$ eq. (iv)

However, equations (i) and (ii) have been simplified as follows:

$i = 0.09T^{\frac{3}{2}}$ eq. (v) and $a = I\left(\frac{1.6}{100}\right) + 0.5$ eq. (vi)

- T = 18, a = 0.6 and I = 6.8

ETP values obtained from rainfall recordings over the period 1983-2013 are presented in table 3.2.

Figure 0.13: Potential evapotranspiration

e) Actual evapotranspiration

Evapotranspiration is the sum of the transpiration of the vegetation cover (through plant stomata) and the evaporation of soils. The actual evapotranspiration (ETR) designates the value of this stream at a given instant or its average over a given period for a given station. The actual evapotranspiration can be estimated using temperature and rainfall data given by empirical formulas:

Turc Formula

$$\boldsymbol{ETR = \frac{P}{\sqrt{(0.9+(\frac{P}{L})^2}}}$$ eq. (vii), where P refers to mean annual rainfall in (mm)

T refers to mean annual temperature in (°C)

L is called Turc coefficient depending on temperature:

$L = 300 + 25T + 0.05T^3$ eq. (viii)

Coutagne Formula

$ETR = P - \lambda P^2$ eq. (ix), where P is the mean annual rainfall (mm) and λ is the regional coefficient depending on temperature and expressed as follows:

$$\lambda = \frac{1}{(0.8+0.14T)}$$

Note: One should remark that Coutagne equation is only valid when:

$$\frac{1}{8}\boldsymbol{\lambda} < P < \frac{1}{2}$$

For this study, Turc formula was used to determine potential evapotranspiration of Fez-Meknes region (*Table 3.3*).

Table 0.3: Actual evapotranspiration estimated by Turc formula

P (mm)	T (°C)	$\boldsymbol{L}$	ETR (mm/yr)
421.7	17.3	991.39	405.61

2.8.7 Season distribution

Ombrothermal diagram of GAUSSEN and BAGNOULS is a graphical method which allows to define the dry and wet periods of the year, where the precipitations (P) and the temperatures (T) are plotted on the abscissa and P = 2T.

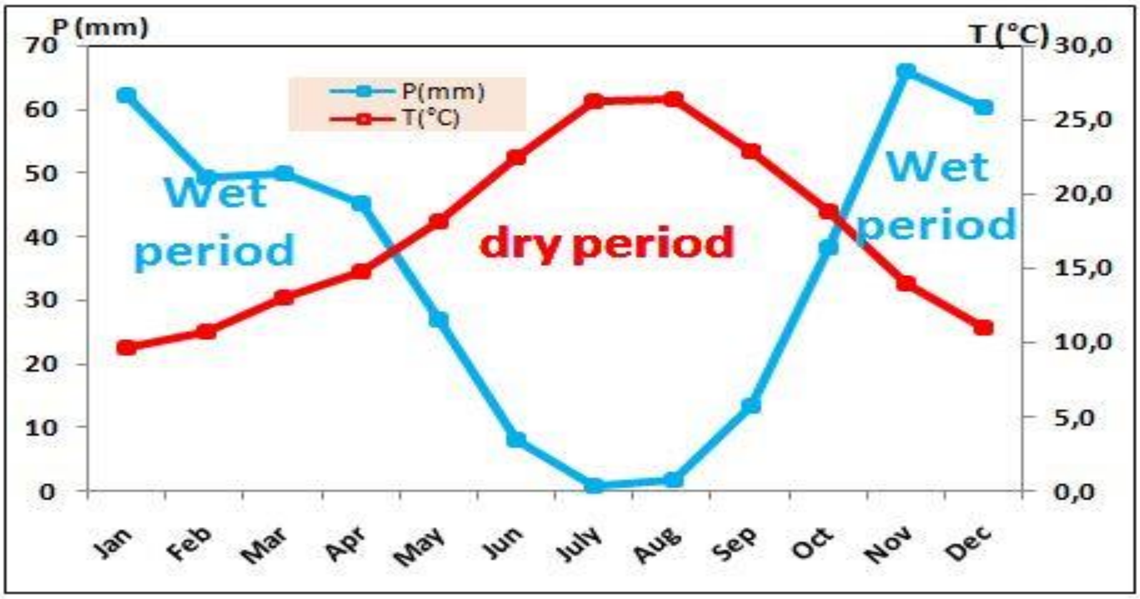

Figure 0.14: Climate period variation

Figure 3.14 shows that climate in Fez-Meknes region is characterized by two periods: A dry period which lasts for almost 4 months occurs between May and September, and a wet season that lasts 8 months and begins in October and ends in May.

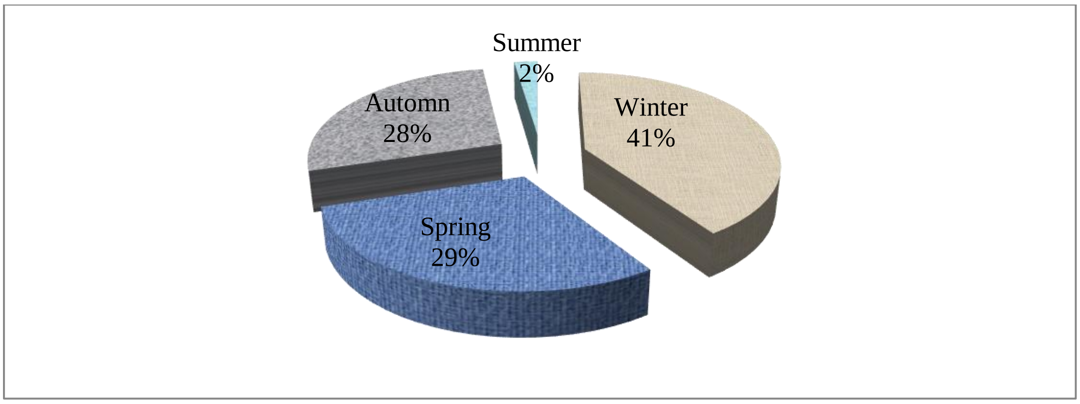

Figure 0.15: Season distribution in Boufekrane watershed

Figure 3.15 shows that climate of Fez-Meknes is distributed between four (4) seasons**.** Analysis of season distribution shows that winter, autumn and spring are the longest seasons whereas summer (2%) is the shortest season. It should also be highlighted that winter and winter and spring are wet seasons while summer and autumn are dry seasons.

2.8.8 Characteristics of Boufekrane watershed

a) Shape

A watershed is mainly characterized by its slope index, perimeter (P), area (A), length (L) and Gravelius coefficient (K_G). Perimeter and area of Boufekrane watershed: They were directly determined by using ArcGIS 10.2 after delineating the boundaries of the watershed. This delineation was made by using Fez topographic map at 1/25 000.

Gravelius coefficient: It is used to characterize the form of a watershed. It is defined as a ratio of the watershed perimeter to that of circle having the same surface. Mathematically it is given by the following formula:

$K_G = \frac{P}{2\sqrt{\pi \times A}}$ eq. (x) where P and A respectively refer to perimeter and area of the watershed.

In the case study of Boufekrane, P = 32 km and A = 33 km^2 and

$K_G = 1.57.$

It can therefore be concluded that Boufekrane watershed is of elongated shape, which makes raindrop reach the watershed outlet with a longer concentration time. The length of the equivalent rectangle is given by:

$$L = \frac{K_G\sqrt{A}}{1.12}[1 + \sqrt{1 - \left(\frac{1.12}{K_G}\right)^2}]$$ eq. (xi) and its width is expressed as:

$$l = \frac{K_G\sqrt{A}}{1.12}[1 - \sqrt{1 - (\frac{1.12}{K_G})^2}]$$ eq. (xii)

In the case of Boufekrane watershed, L = 13.7 m and l = 2.41 m

b) Spatial distribution of elevations

In order to better describe the topography and understand the spatial distribution of altitudes in Boufekrane watershed, a Digital Elevation Model (DEM) was used. The Digital Elevation Model of Boufekrane watershed in *Figure 3-16* shows that altitudes of the watershed are between 394 m and 655 m. It also reveals that the southern part of the watershed is higher than the northern part. It can be inferred that the southern part of the watershed is the upstream whereas the north is the downstream where is located the watershed outlet.

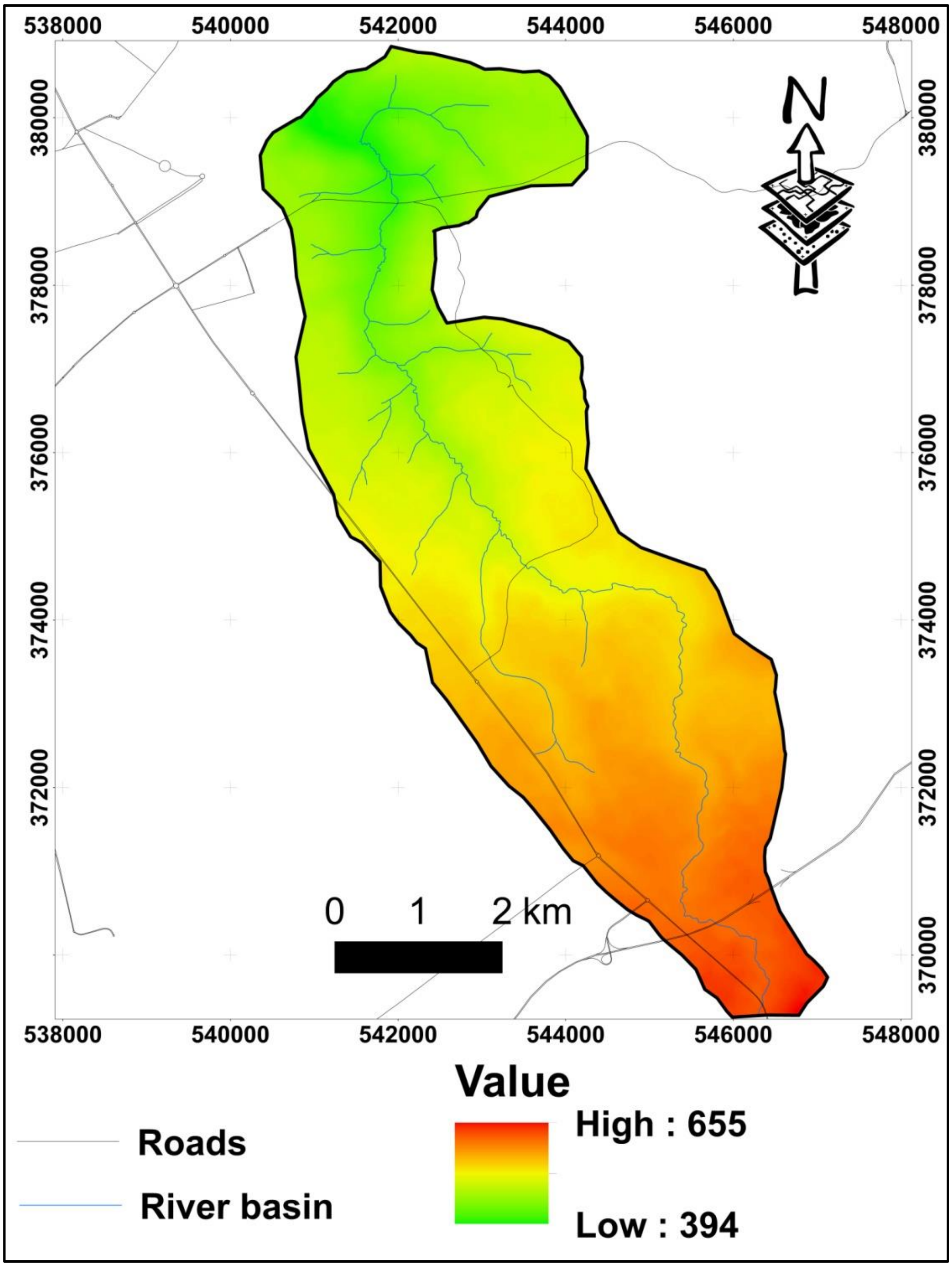

Figure 0.16: Digital Elevation Model of Boufekrane Watershed

c) Hypsometric curve

The hypsometric curve of the watershed is generated according to the following steps:

- Classification and reclassification of altitudes by using ArcGIS (Arc Toolbox). Five (05) classes of elevation were defined based on grid codes corresponding to elevation intervals: [394 - 448], [448 - 492]; [492 - 539]; [539 - 585]; [585 - 655].
- Calculation of areas of altitude classes
- Determination of partial area of each elevation class surface in percentage by using the following simple formula:

$$Partial\ Area\ (\%) = \frac{Elevation\ class\ area\ (km^2)}{Total\ area\ of\ the\ watershed\ (km^2)} \times 100 \quad \text{eq. (xiii)}$$

- After partial altitude classes area have been determined, cumulative percentages were determined from calculated partial areas. The hypsometric curve is then obtained by plotting elevations (m) versus cumulative percentages (%).

Table 0.4: Altimetry data of Boufekrane watershed

	Area (km^2)	**Altitude (m)**	**Percentage (%)**	**Cumulative percentage (%)**
	0	655	0	0.00
394 – 448	4.19	585	12.70	12.70
448 – 492	7.21	539	21.85	34.55
492 – 539	8.22	492	24.91	59.46
539 – 585	8.22	448	24.91	84.37
585 – 655	5.16	394	15.63	100

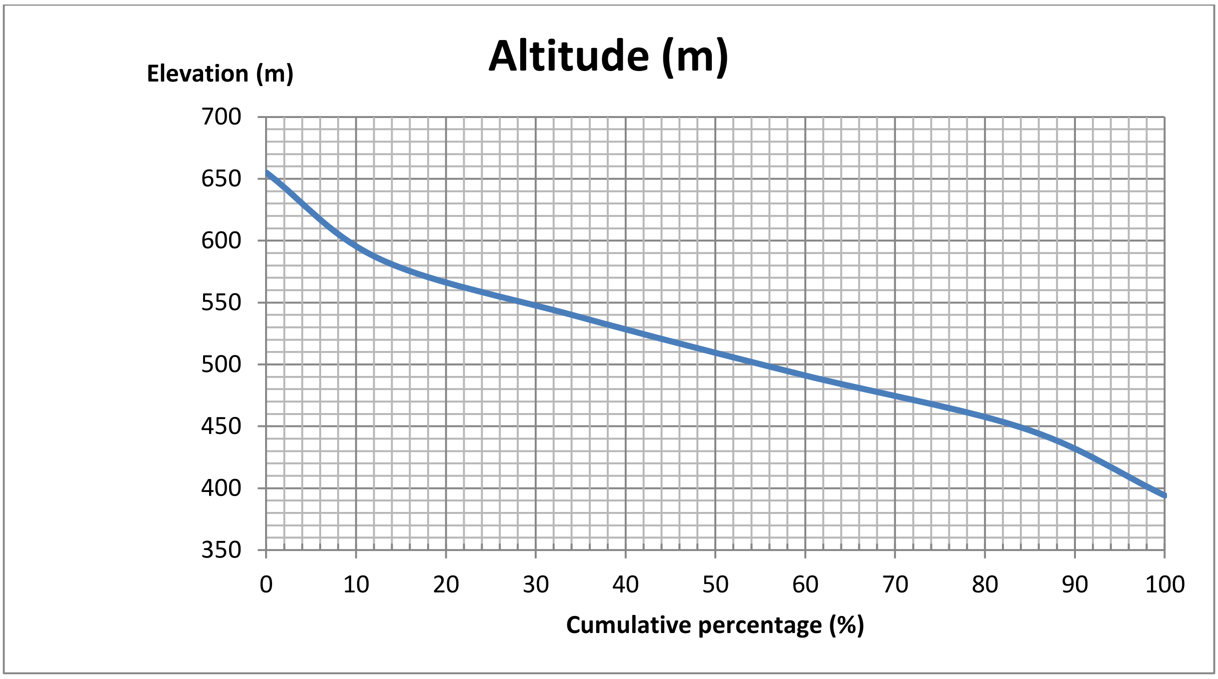

Figure 0.17: Hypsometric curve of Boufekrane

The obtained hypsometric curve in figure 3.17 shows that:

- 44% of the total watershed area is of altitudes between 400 m and 500 m
- 14% of Boufekrane is of high altitudes (Altitudes ≥ 580 m) and altitudes (Altitudes between 450 and 580 represent 68% of the total watershed area
- The lowest altitudes (less than 400 m) only represent 2% of the total area of the watershed.

Table 0.5: Characteristic altitudes of Boufekrane

Parameters	Meter (m)
Maximal altitude	655
Minimal altitude	394
Altitudes > 5% of Boufekrane area	620
Altitudes < 95% of Boufekrane area	407
Theoretical difference elevation (ΔH)	261
Average elevation (H_{avg}) (1)	521.48

[1] The average elevation was determined by using the following equation

$H_{moy} = \sum \frac{A_i \times H_i}{A}$ eq. (xiv) where A_i: partial area of elevation class, H_i: mean altitude of elevation class and A: Total area of watershed.

The average altitude is approximately 521.48 m while median altitude which corresponds to elevation of 50% of the total watershed ($H_{50\%}$) is 488m. Difference between average and median altitudes suggests that Boufekrane is of irregular slope. Gravelius coefficient and dimensions of the watershed equivalent rectangle (L = 13.7 m and l = 2.41 m) suggest that Boufekrane is not well-drained.

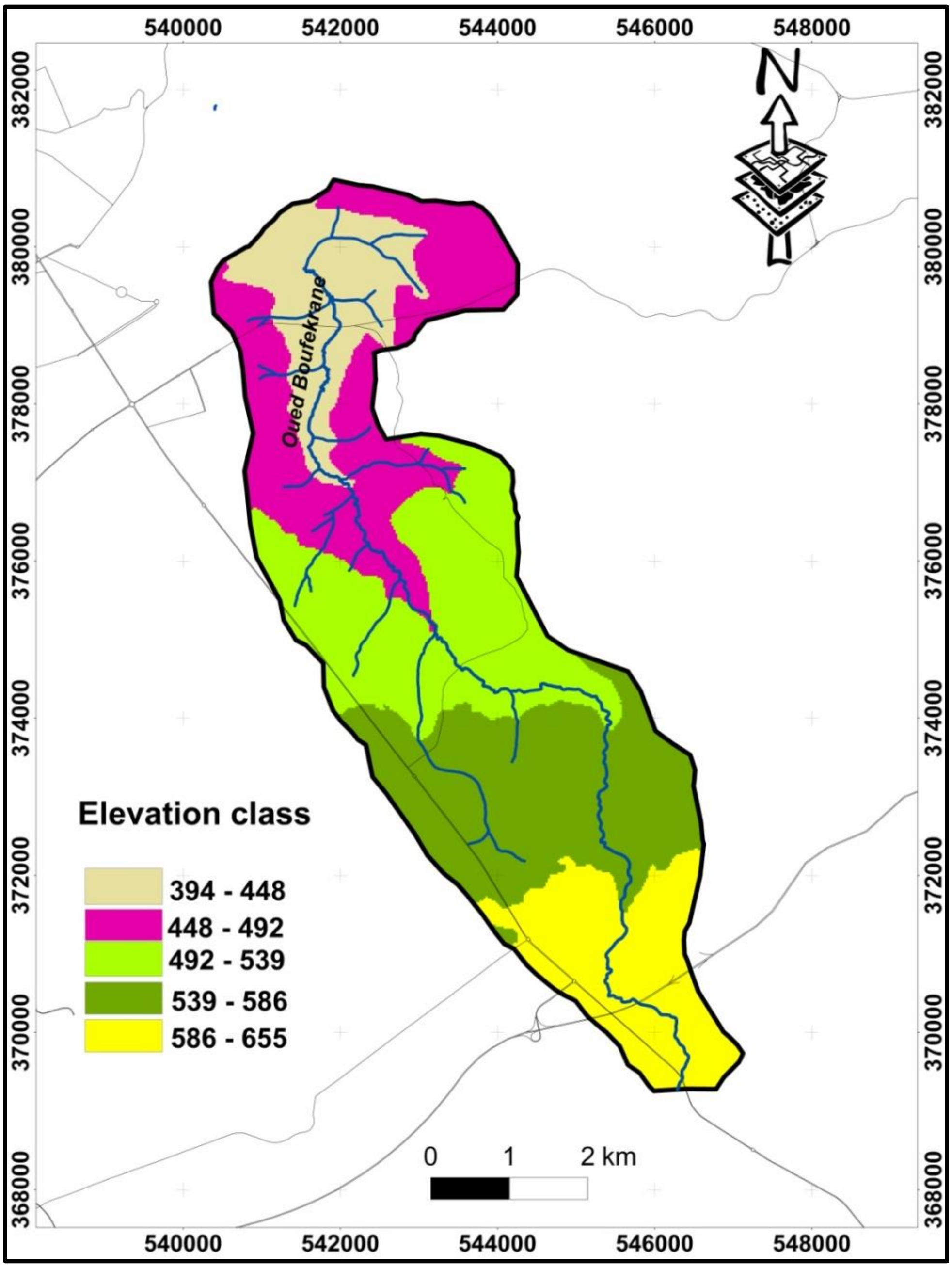

Figure 0.18: Hypsometric map of Boufekrane Watershed

d) Spatial distribution of slope

Slope map of Boufekrane was obtained by processing the Digital Elevation Model of the watershed with GIS. Classification of slopes (expressed in percentage) was made based on guidelines defined by PAP/RAC and UNEP, in collaboration with the Directorate General of Nature Conservation (DGCONA) of the Ministry of Spanish Environment, Land and Water Development and the Division of the Food and Agriculture Organization of the United Nations (FAO). Globally, Boufekrane slopes are low to moderate. Steep slopes only account for less than 1%. Analysis of slope distribution shows that very low to moderate slopes are the most represented (table 3.6). Areas of flat to low steep slopes cover 19.52 km2 which represents 58.89% of the total area of watershed. Moderately steep slopes accounts for 41.11%. All this tends to prove and that Boufekrane is located in a region of plains.

However, it is possible to better characterize slopes of a given watershed by using some parameters.

Table 0.6: Slope classes of soils in Boufekrane

2.8.9 Conclusion

a) Climate

From analysis of data of Saiz-Fez region climate, it was apparent that there is an alternating relationship between wet and dry seasons. Periods of extreme temperature (high temperatures) coincide with months of lowest rainfall patterns (figure 3.10). This characteristic is the main difference between Mediterranean and Sahel regions.

Analysis of climatic parameters enables the following remarks:

Slope class	Range	Type of slope	Area (km^2)	Accounts for (%)
1	0-3%	Flat to low	19.52	58.89
2	3%-12%	Moderate	13.63	41.11
3	12% -20%	Steep	0.002	0.0074
		Total	**33**	**100.0**

- The average inter-annual precipitation obtained over the period 1980-2014 is 421.7 mm.

- Analysis of seasonal precipitation of Fez-Meknes region shows that winter and spring are the wettest periods while summer is the driest season.

- Mean monthly precipitation is estimated to 35.14 mm.

- November with a rainfall of 64.6 mm is the wettest month while the month of July is the driest month with a precipitation of 0.7 mm.

- For temperatures, January is found to be the coldest month (9.6 °C) while August is the hottest month (26.3 °C).

b) Spatial distribution of altitudes

Geomorphologic analysis showed that Boufekrane watershed is characterized by low to moderate altitudes (do not exceed 700 m). This tends to prove location of Boufekrane in a region of plains.

2.9 Soil Erosion Assessment by PAP/RAC Model

In order to perform soil erosion risk mapping, numerous documents within the PAP/RAC erosion control framework were downloaded. It was apparent that methodology of soil erosion risk assessment should be achieved in three phases. The first phase, called predictive approach, aimed at determining the susceptibility of a soil to erosion due to physical parameters recognized to influence soil erosion. The second approach, called descriptive approach consisted of identifying current on-site and actual forms of erosion that exist in the catchment. The last phase of the study called consolidated approach provided final information of soil erosion risk status combining both predictive and descriptive information**.** Basically, this final phase consisted to combine information on erosivity status determined from predictive approach and current on-site erosion forms identified in descriptive phase, this in order to produce a final map that states the risks of erosion, actual erosion processes as well as erosion process expansion trends.

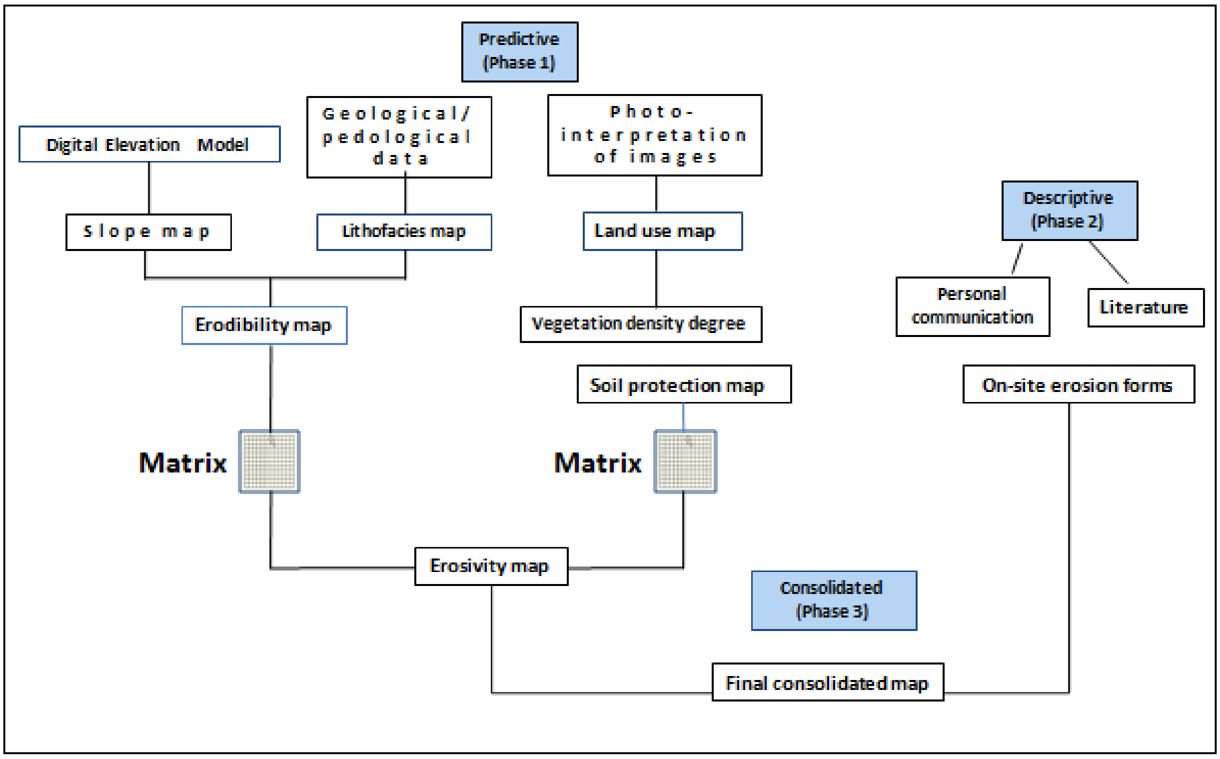

Figure 0.19: Flow chart of PAP/RAC model erosion mapping (PAP/RAC, 1997)

2.9.1 Predictive approach

It reflects the potential state of erosion susceptibility of a soil due to its physical factors. This approach consists of identifying, analysing, integrating and assessing major parameters recognized to influence soil erosion. In the scope of this study, slope, lithology and vegetation cover were considered as major factors of soil erosion in Boufekrane watershed. The aim and final output of this phase is to obtain an erosivity map establishing preliminary hypothesis of soil erosion risks. The predictive approach consisted of three phases.

a) Elaboration of erodibility map

Soil erodibility expresses its potential to resist to erosion (Morgan, 2005). It therefore takes into account soil friability and slope steepness. In PAP/RAC model, erodibility map was obtained by overlaying slope and lithofacies maps.

i) Slope map

Slope map was obtained by generating slopes from the Digital Elevation Model of Boufekrane according to PAP / RAC guidelines. Table 3.7 shows classification of slopes according to PAP/RAC guidelines.

Table 0.7: Slope ranges defined by PAP/RAC guidelines

Slope class	Slope type
1	Flat to low (0-3%)
2	Moderate (3% -12%)
3	Steep (12% - 20%)
4	Very steep (20%-35%)
5	Extremely steep (>35%)

(PAP/RAC, 1997)

ii) Lithofacies

Lithofacies analysis was performed by using different data including geological, lithological and pedological information. PAP/RAC guidelines provide a classification of soil types. Each soil type is associated with a letter that describes resistance, cohesiveness and constitution of the soil. Table 3.8 details how soils were classified according to their types.

Table 0.8: Classification of lithofacies by PAP/RAC guidelines

Class	Material type
(a)	Non compacted compact rocks, strongly cemented conglomerates, crusts, ferruginous sandstone outcrops (massive limestone, strongly rocky soils, igneous or eruptive rocks, locally encrusted soils)
(b)	Broken or moderately altered cohesive rocks or soils
(c)	Rocks or sedimentary soils weakly or moderately compacted (slate, schist, marl, etc.)
(d)	Rocks and/or soils not very resistant or strongly altered
(e)	Sediment or loose soil, non cohesive and detritus material

ii) Erodibility map

As described before, erodibility map is obtained by overlapping slope map and lithofacies map. This is done by applying the matrix presented in table 3.9 proposed by PAP/RAC guidelines. Each erodibility grade obtained is classified according to PAP/RAC directives as described in table 3.10.

Table 0.9: Matrix of slope vs. Lithofacies

	Lithofacies class				
Slope class	**(a)**	**(b)**	**(c)**	**(d)**	**(e)**
1	1	1	1	1	2
2	1	1	2	3	3
3	2	2	3	4	4
4	3	3	4	5	5
5	4	4	5	5	5

Table 0.10: Erodibility classification by PAP/RAC

Class	Erodibility status
1	very low
2	Low
3	Moderate
4	High
5	Extremely high

b) Elaboration of soil protection

Soil protection map was obtained by overlaying land use map and vegetation cover density according PAP/RAC directives.

i) Land use map

Land use map was obtained from Google Earth satellite image of this region which was downloaded by Terra Incognita software and digitized by using ArcGIS. Then, classification of land use classified into attributes based on nature of polygons was based on PAP/RAC guidelines. For the purpose of this study, Boufekrane watershed land use was classified into four groups: Habitats, arable lands, cultivated areas and pastures. Table 3.11 provides the PAP/RAC land use classification used in the scope of the study.

Table 0.11: Land use classification by PAP/RAC

Classes	Land use
1	Arable lands
2	Cultivated areas (Olive, almond, fruit trees, vineyards, etc…)
3	Irrigation schemes
4	Forests
5	Dense shrubs
6	Pastures, Sparse shrubs

Studies on changes in land use and use are of great importance as they provide insights to on current trends in deforestation, soil degradation expansion, desertification and loss of biodiversity in a particular region.

ii) Vegetation density map

Map of vegetation cover density was obtained by applying PAP/RAC classification presented in table 3.12. PAP/RAC classifies levels of vegetation cover into four classes: 1, 2, 3 and 4. In this study, identification of vegetation cover density of Boufekrane watershed was performed by observations of satellite image. It was considered according to PAP/RAC directives that cultivated areas covered by tree crops have density class between 25% and 50%. The rest of land cover in Boufekrane assumed to be of relatively low density class (less than 25%).

Table 0.12: Classification of cover level by PAP/RAC

Classes	Degree of vegetal cover
1	Less than 25%
2	25%-50%
3	50%-75%
4	Larger than 75%

iii) Protection map

This map was obtained by overlapping land use map and vegetation cover map. The map of soil protection level is obtained by applying the matrix presented in the table 3.13. Five classes of protection level were defined according to PAP/RAC guidelines. Class (5) refers to a very low status of soil protection level, class (4) refers to a low status of soil protection level, class (3) for moderate soil protection level, class (2) for a high level of soil protection, and class (1) refers to a very high soil protection level. However, in order to better simulate soil erosion process in Boufekrane watershed, an additional class of soil protection level was added: Class (**0**) refers to protection level in high impervious surface areas due to urbanization processes as a result of socio-economic development.

Table 0.13: Matrix of land use type vs. vegetation cover by PAP/RAC

Land use type	**Vegetation cover**			
	1	**2**	**3**	**4**
1	5(MB)	5(MB)	4(B)	4(B)
2	5(MB)	5(MB)	4(B)	3(M)
3	3(M)	2(A)	1(MA)	1(MA)
4	4(B)	3(M)	2 (A)	1(MA)
5	5(MB)	4(B)	3(M)	2(A)
6	5(MB)	4(B)	3(M)	2(A)

c) Erosivity

Erosivity map is the final output of predictive approach. Erosivity status is obtained from the overlapping of erodibility map and soil protection level map. Overlaying operations were done by applying the matrix presented in the **table 3.14**. Five (05) classes of erosivity status are defined by the PAP/RAC methodology. Class (1) refers to a very low status of erosivity, class (2) for low erosivity level, class (3) for moderate erosivity status, class (4) for high erosivity, and class (5) refers to a very high level of soil erosivity. One should remark that PAP/RAC did not include stable areas to define erosivity status. Regarding the use of colours, PAP/RAC guidelines recommend the following colours:

- Stable areas not affected by erosion must be presented in blue or green.
- Unstable areas are displayed progressively in yellow, orange, light red or dark red, gradually increasing the density of the chosen colours (dots to full colours).

Table 0.14: Matrix of Erosivity

	Erodibility				
Level of soil protection	1(EN)	2(EB)	3(EM)	4(EA)	5(EX)
1(MA)	1	1	1	2	2
2(A)	1	1	2	3	4
3(M)	1	2	3	4	4
4(B)	2	3	3	5	5
5(MB)	2	3	4	5	5

Table 0.15: Ranks and descriptions of erosivity status

Erosivity grade	Description of erosivity
1	Very low
2	Low
3	Moderate
4	High
5	Very high

2.9.2 The descriptive method

This approach consisted to identify and describe actual forms of soil erosion in the watershed. In this study, identification of on-site erosion forms was performed by personal communication and from available literature on Morocco's case studies given that field check was not possible to be carried out. GIS software was used to establish a spatial distribution of actual erosion forms. As with predictive phase, descriptive method is performed in distinct steps:

a) Stable areas

As defined by PAP/RAC, this phase only applies to stable areas where erosion is inexistent, not noticeable or very low. Those are areas with well-developed surface horizons and good soil structure. They are in most cases poorly exploited by man where there is no unsustainable anthropogenic activity susceptible to affect soil stability. Moreover, vegetation cover is optimal and topographical conditions do not favour erosive processes. The level of stability is determined by three (03) classes ranging from **0** (referring to areas with no erosion risk) to **3** (referring to the highest soil erosion risk. This step was not addressed since in Boufekrane watershed there is no area that met the above criteria.

b) Unstable areas

This phase consisted to identify and define predominant erosion processes occurring in the watershed. All unstable areas affected by one or more low, moderate to severe erosion processes were identified from personal communication. Then, assessment and description of erosion processes were made regarding their intensity and nature based on PAP/RAC guidelines. The following descriptions are proposed within the PAP/RAC guidelines:

- Sheet erosion forms: They are represented by L1, L2, L3 or LX according to intensity of erosion processes. For instance, L1 (sheet erosion of minor intensity) is characterized by a localized and slight surface leaching due to rain splash and runoff. This soil removal corresponds to a soil loss rate slightly greater than that of its formation; L2 refers to moderate sheet erosion resulting in a loss of localized arable lands especially in cultivated areas or areas with low vegetation cover; LX (the most severe form of sheet erosion) results in total removal of soil and non-recoverable lands. These areas are called Badlands.

- Rill erosion: It is represented by letter “D”. It occurs when sheet erosion is not handled very well. Minor forms of rill erosion (D1, D2) are generally erased by tillage practices.

- Mass earth movements: They are represented by letter “M” and appear everywhere where there are marls. It minor form (M1) corresponds to gravitational soil creep or solifluction. The most severe form of mass movements is a total loss of soil due to total slope slide (MX).

- Gully forms: In the PAP/RAC guidelines, they are symbolized by “C” letter. They range from individual gullies (C1) to non-recoverable lands due to generalized gullies (CX).

Note: Roads, habitats and other urban infrastructures are not deteriorated and then were assumed to be non-affected by soil erosion processes.

Table 0.16: Grade of stability defined by PAP/RAC (step 1)

Stable	00	Stable, non-used wasteland (Rock, outcrops, cliffs, stony or sandy areas)
Non-erosion-affected areas	01	Stable, unmanaged areas with potential for forestry use only
	02	Stable, unmanaged areas with agricultural potential (crops and pasture)
	03	Stable, managed areas for forestry use only
	04	Stable, managed areas with agricultural use (crops and pasture)
Rehabilitated areas	05	Natural or artificial re-vegetation
	06	Physical infrastructures (check dams, terraces, etc…)

Table 0.17: Site-descriptive mapping of unstable areas by PAPA/RAC (step 2)

L	**Sheet erosion**
D	Rills erosion
C	Gullies erosion
M	Mass earth movements
L1, L2, L3,..., LX	Localized sheet erosion to non-recoverable lands due to total soil loss
D1, D2,D3,...DX	Localized to generalized rills
M1, M2, M3,...MX	Localized gravitational soil creep to total soil loss due to severe slope slides

2.9.3 Consolidated approach

This phase outputs a map which results from integration of erosivity data obtained in the predictive approach (phase1) and data of on-site erosion processes obtained in the descriptive approach (phase 2). This final input aims at mapping current and potential erosion risks as means to identify priority areas for action and strategies for anti-erosive (erosion control) and land management programmes.

a) Elaboration of consolidated map

Erosivity map and site-descriptive map were overlapped to produce the consolidated map. Description and mapping of actual erosion and erosion risks are complementary to the data provided by the predictive mapping, which would mean that the final diagnosis of erosion must be expressed by a unique and integrated symbol.

b) Assessment of erosion expansion process

This evaluation of erosion process expansion only concerns unstable areas of the watershed. PAP/RAC directives were used as guidelines and methodology framework to assess the trend of soil process development in Boufekrane watershed. Grades of assessment range from 1 to 4. Each grade expresses a particular development of the affecting erosion process.

Table 0.18: Trend of erosion process expansion

Erosivity	**Actual erosion** Minor erosion forms (L and D)	Major erosion forms (C1...,CX)
Very low: 1	1	3
Low: 2	1	3
Moderate: 3	2	4
High: 4	2	4
Very high: 5	2	4

Grade (**1**) refers to a stabilization, or recession or limitation trend. Grade (**2**) is attributed to unstable areas with expansion or intensification trend of erosion processes. Grade (**3**) refers to a widespread erosion expansion or intensification trend. Grade (**4**) refers to a trend of increased generalized soil degradation towards an irreversible state.

2.10 Data Collection

2.10.1 Soil data

a) Geological and pedological maps

Both geological and pedological maps were required to produce lithofacies map required for predictive phase (Phase 1). Geological map was obtained from 1974 Sefrou geological map at the scale of 1/100 000 and 1967 Fez geotechnical map (1/20 000). The map of Boufekrane pedology was in turn available.

2.10.2 Altimetry data

A Digital Elevation Model of Boufekrane was required to have a spatial distribution of altitudes in the watershed, but also was needed to create a slope map. DEM of the region with a resolution of 30 m on which Boufekrane was already delineated was available and obtained from the Laboratory of Geo-Resources and Environmental Sciences (LGRES) of Faculty of Sciences and Techniques (Fez).

2.10.3 Vegetation data

Data of NDVI were available and obtained from the Laboratory of Geo-Resources and Environmental Sciences (LGRES) of Faculty of Sciences and Techniques (Fez). This data set for the years 1976 to 2006 was used for trend analysis.

2.10.4 Long term climatic data

Long term climatic data (including rainfall and temperature) for Boufekrane watershed were available from LGRES and obtained from DRH Fez gauge station (X=53540, Y=38480, Z=415) having the identifying code of 3817. Data were available from the SRBA. Data over the period 1985 – 2014 were collected although data of earlier years were available.

a) PAP/RAC guidelines

Guidelines of PAP/RAC are the core database of this study since it provides all directives required for soil erosion mapping. PAP/RAC documents on soil erosion assessment were obtained from Google Scholar.

Chapter 4:
RESULTS AND DISCUSSION

3.1 Predictive Approach

3.1.1 Slope map Analysis of slope map (figures 4.1 and 4.2) shows that Boufekrane watershed is mainly dominated by very low steep slopes (0-3%). They cover an area of 19.43 km^2 accounting for 58.89% of the total area. Moderate slopes (between 3% and 12%) cover an area of 13.57 km^2, which accounts for 13.57% of the total area watershed. High steep slopes (slopes between 12-20%) are marginally represented and are found in upstream. They account for less than 1% of the total watershed area. All this tends to prove the situation of Boufekrane in a region of plains.

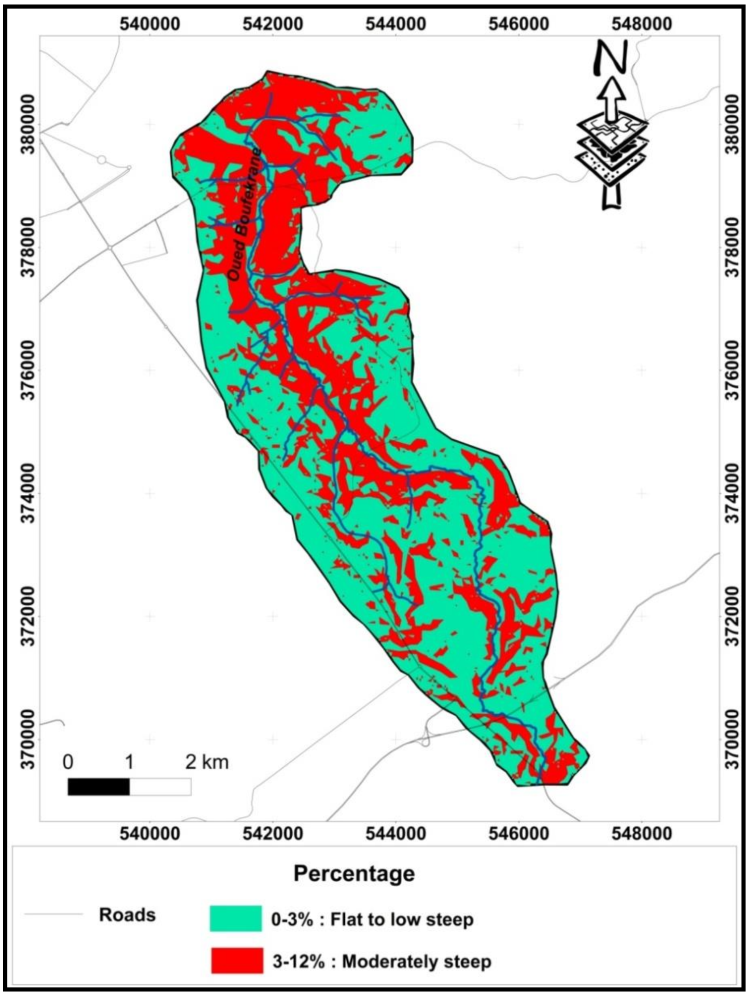

Figure 0.1: Slope map of Boufekrane

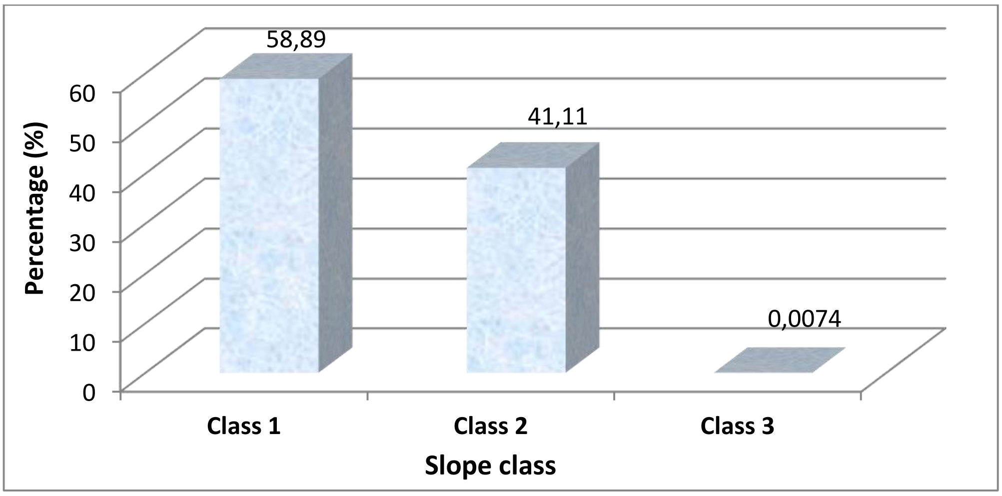

Figure 0.2: Chart of slope classes and percentages

3.1.2 Lithofacies

The friability map illustrated in figure 4.3 shows that Boufekrane soil is mainly formed of cemented conglomerates (a). They cover 78% of the total area. Deeply altered and little resistant soils (d) cover an area of 5.12 km^2 which represents 15.51% of the total watershed area.

Table 0.1: Soils lithofacies of Boufekrane

Class of lithofacies	Area (km^2)	Accounts for (%)
Cemented conglomerates (a)	25.74	78
Moderately altered soil (b)	0.20	0.61
Weakly compacted rocks (c)	1.94	5.88
Deeply altered (d)	5.12	15.51
Total	**33**	**100**

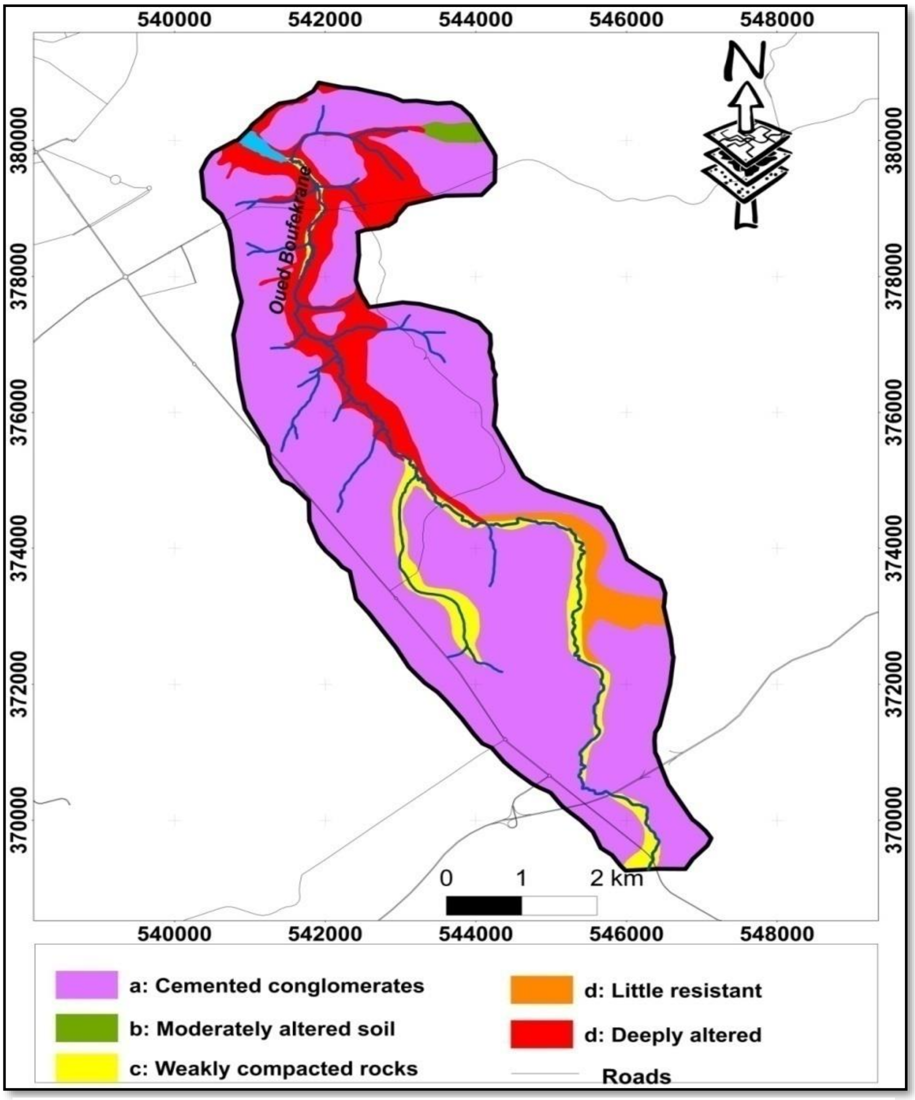

Figure 0.3: Lithofacies of Boufekrane

3.1.3 Erodibility

Results showed that erodibility is important everywhere where slopes are relatively important and where soils are fragile. It was apparent that only 3 km^2 (9.08% of the total watershed area) are of moderate to high erodibility and are found for slopes between 3-12% and for deeply altered soils (lithofacies of class d). It was also found that 29.51 km^2 (89.42% of the total watershed surface) is of very low erodibility (class 1). Class (2) which refers to low erodibility accounts for 1.50% of the total surface (0.49 km^2). Low erodibility is observed in areas with cemented conglomerates.

Table 0.2: Soil erodibility distribution of Boufekrane

Erodibility	Surface (km^2)	Accounts for (%)
1 (EN)	29.51	89.42
2 (EB)	0.49	1.48
3 (EM)	2.99	9.07
4 (EA)	0,01	0.03
Total	33	100

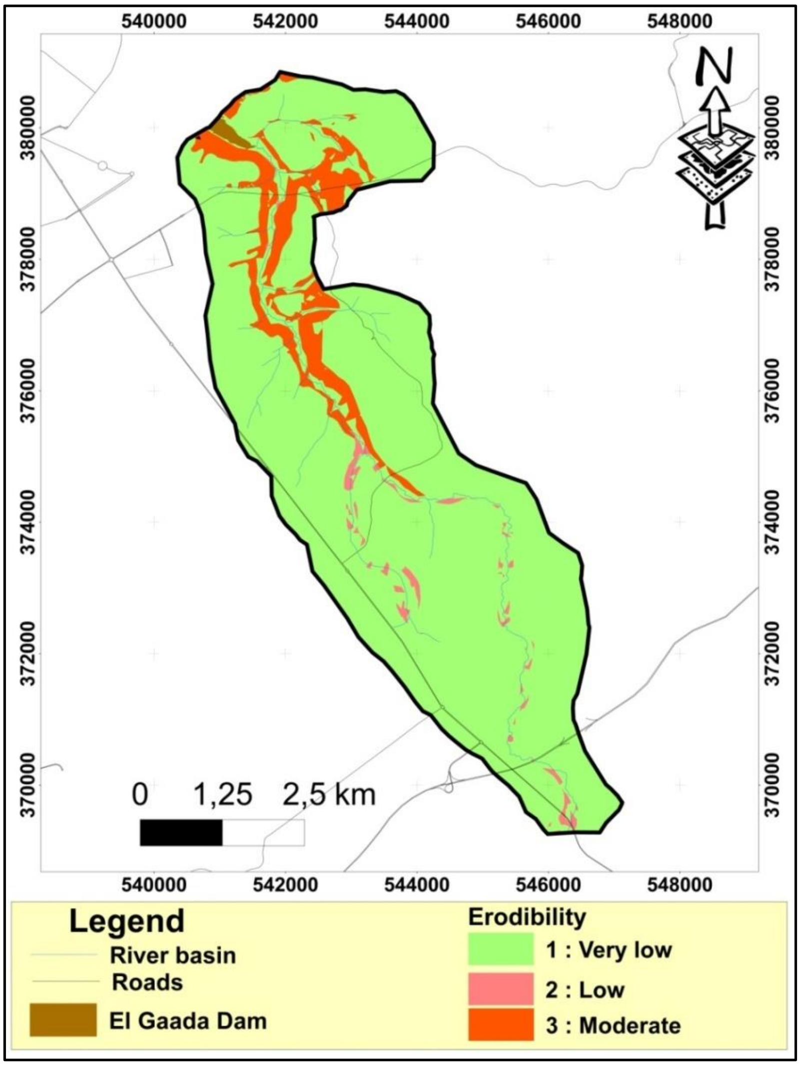

Figure 0.4: Erodibility map of Boufekrane watershed

3.1.4 Land use / change

Globally, it clearly emerges from land use analysis that Boufekrane watershed is composed of two broad units:

- Areas not affected by erosion including habitats and roads cover 450 ha (13.63% of total area).
- Areas affected by erosion including arable lands meant for cereal crops (rice, wheat, maize), cultivated areas occupied by olives and fruit trees, pasture areas, meant for grazing activities. The occupation distribution is as follows: Arable lands cover 18.32 km^2 which accounts for 55.52% of the total area. The cultivated areas occupied cover 9.83 km^2, which accounts for 29.79% of the total watershed area. Pastures represent 1.06% of the total area. It should also be mentioned that Boufekrane has a dam covering 0.12 km^2. The agricultural nature of Boufekrane watershed makes it highly prone to erosion process because agricultural practices play a major role in development and acceleration of rainfall induced erosion.

Table 0.3: Distribution of land use Boufekrane

Class	Land use	Area (km^2)	Accounts for (%)
0	Habitats	4.50	13.63
1	Arable lands	18.32	55.52
2	Cultivated areas	9.83	29.79
6	Pastures, Sparse shrubs	0.35	1.06
	Total	**33**	**100**

Analysis of land use in Boufekrane shows that arable and cultivated lands cover an area of 28.15 $km^{2,}$ which represents more than 85% of the total watershed area. Urban areas only accounts for 13.63% of the total watershed area. All this goes to prove that Boufekrane is an agricultural area with a dominance of arable lands which are more vulnerable to erosion.

Table 0.4:Distribution of cover level in Boufekrane

Class	Level of vegetation cover	Area (km^2)	Accounts for (%)
1	Less than 25%	25.02	75.82
2	25%-50%	7.98	24.18
	Total	**33**	**100**

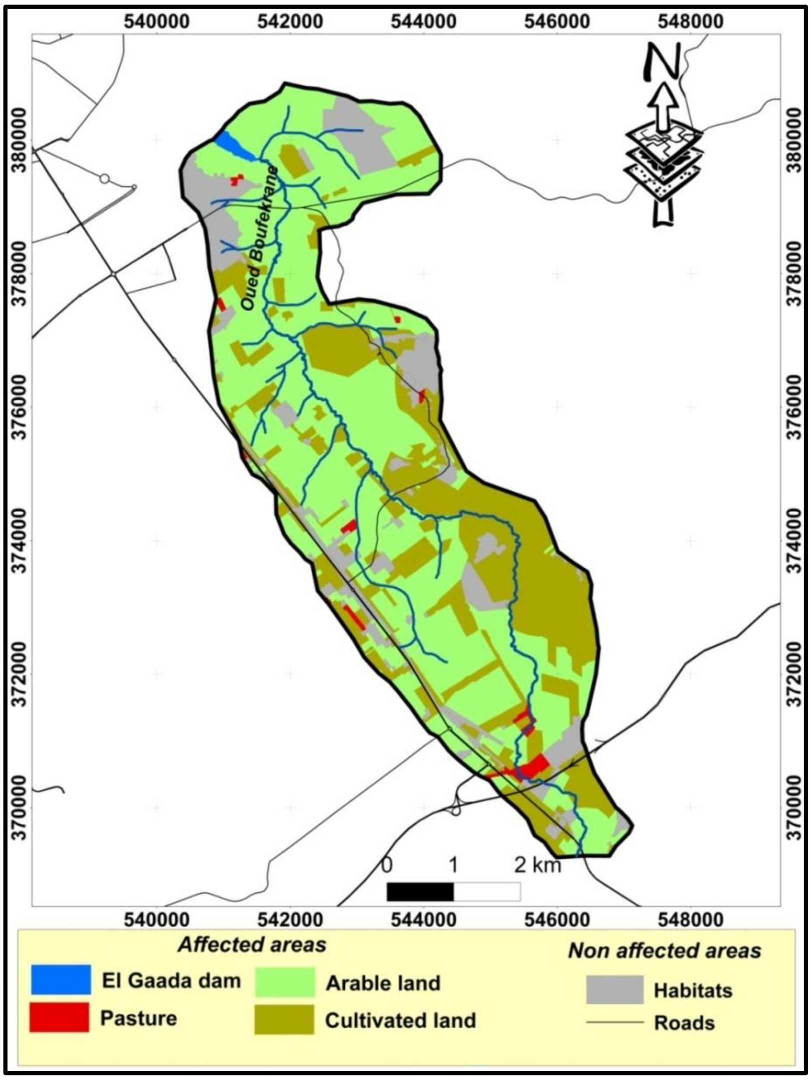

Figure 0.5: Land use of Boufekrane

3.1.5 Vegetation cover status

Data analysis of vegetation cover level reveals that Boufekrane is of low vegetation level. This can be related to dominance of agriculture characterized by cereals and fruit tree crops. Yet those crops are not dense in terms of vegetation.

3.1.6 Soil protection map

In general, it appears that Boufekrane soil is poorly protected. Grade 5 (MB) referring to a very low level of soil protection covers 86.91% of the total watershed area. The spatial distribution of soil protection status revealed that low-protection areas are found everywhere in the watershed: Class (**0**) refers to stable areas protection level in high impervious surface areas due to urbanization processes as a result of socio-economic development. Stable areas only account for 4.50% of the total surface of the watershed. All this goes to prove that Boufekrane watershed is mainly of very low protection status.

Table 0.5: Protection level of soil in Boufekrane watershed

Level of soil protection	Surface (km^2)	Accounts for (%)
5(MB)	28.68	86.91
4(B)	0.0009	0.0027
0	4.32	13.09
Total	**33**	**100**

As suggested by figure 4.6, one can say that Boufekrane is of very low protection level. Such situation can increase the erosivity status of the watershed. Moreover, presence of river basins in the watershed can contribute to enhance its erosivity.

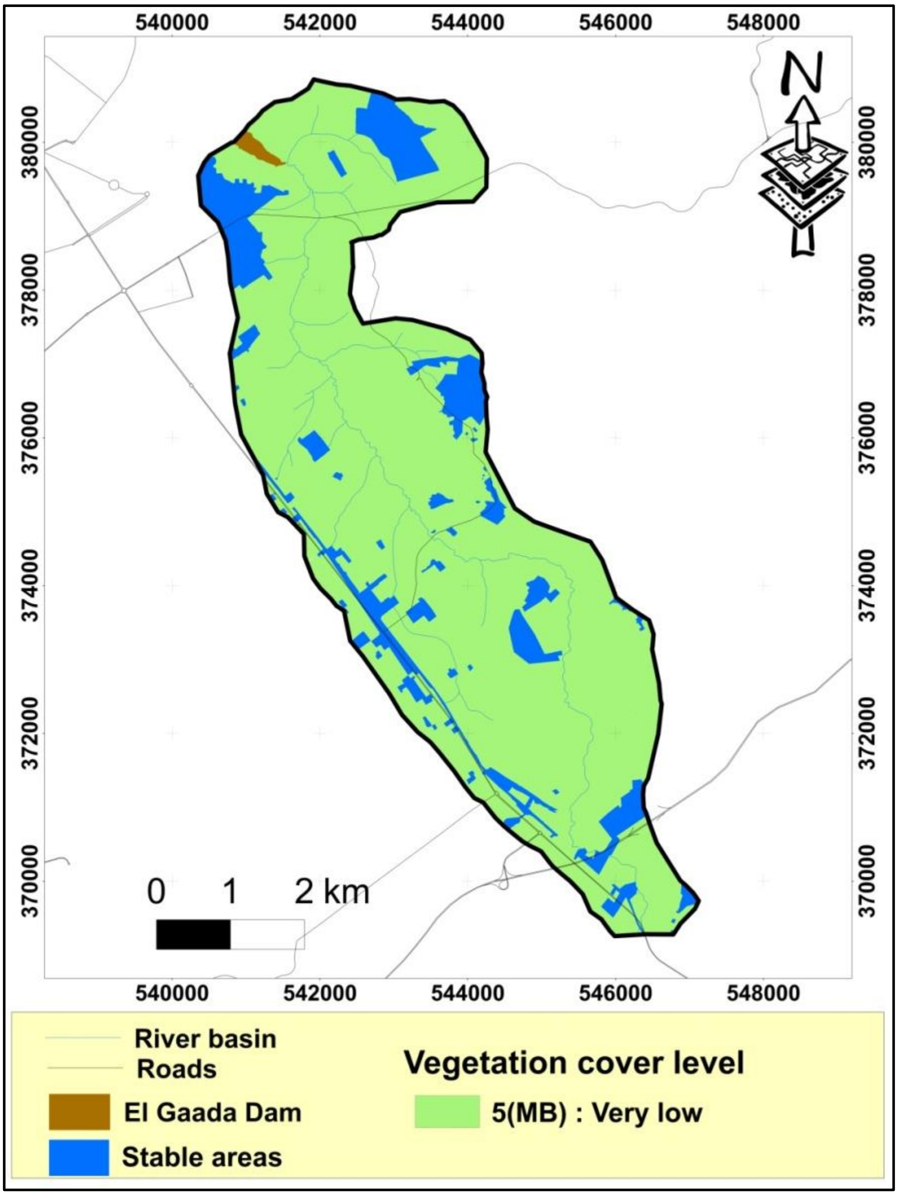

Figure 0.6: Soil protection map of Boufekrane

3.1.7 Soil erosivity

The map of erosivity shown in figure 4.7 is a synthesized qualitative map integrating both erodibility and land protection data. The spatial distribution of erosivity states showed that high erosion occurs mainly in downstream (Northern part of the watershed). Moreover, high erosion risk patterns are concentrated around basin river networks flowing in Boufekrane watershed. It should also be highlighted that areas of significant erosion risk levels are areas with slope of moderate to high steepness.

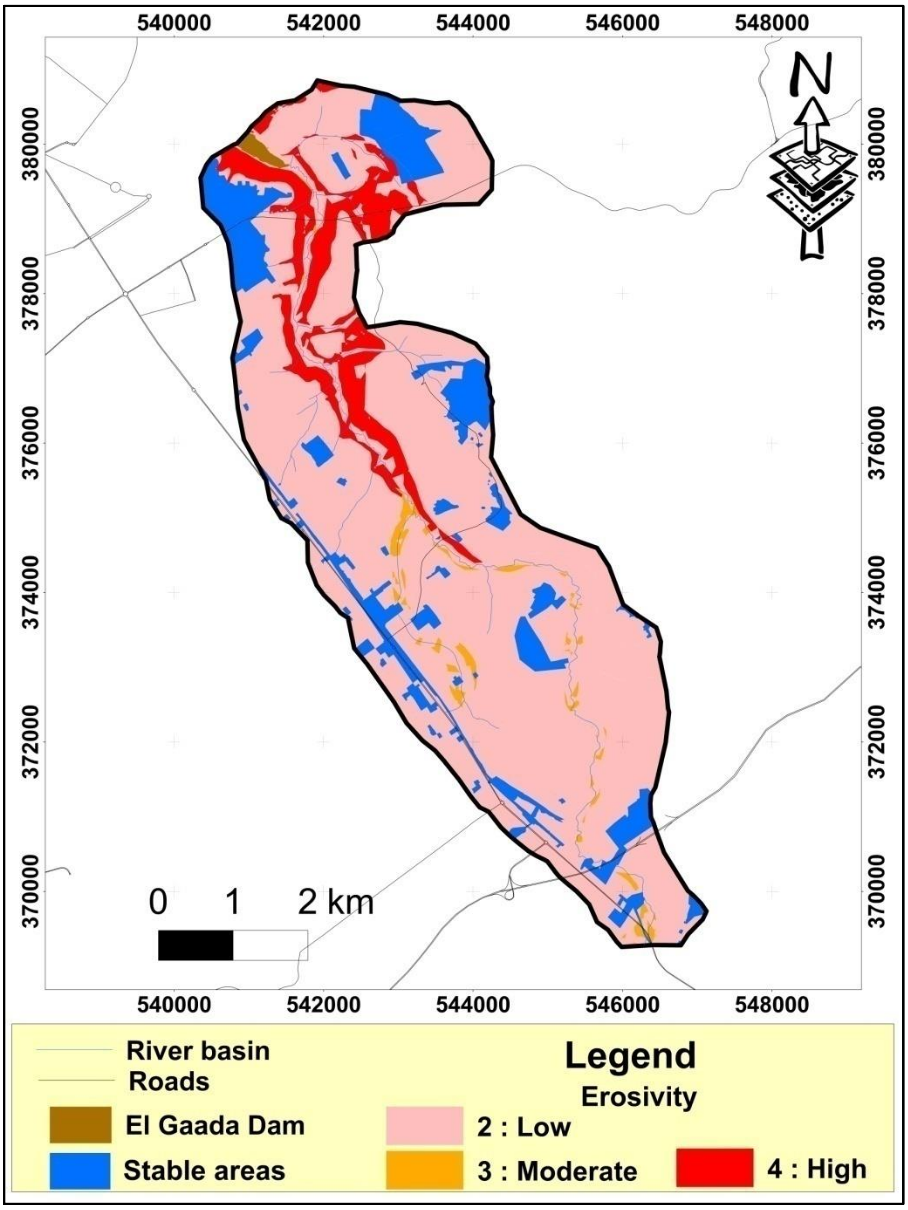

Figure 0.7: Soil erosivity status of Boufekrane watershed

Analysis of erosivity status of Boufekrane shows that the watershed is mainly of low erosivity (76.70%). High to very high erosivity areas only cover 8.15% of the total watershed area (table 4.6 and figure 4.8).

Table 0.6: Erosivity state of Boufekrane watershed

Erosivity class	Surface (km^2)	Percentage (%)
0 : Stable areas	4.56	13.82
2: Low	25.31	76.70
3: Moderate	0.44	1.33
4: High	2.68	8.12
5: Very high	0.01	0.03
Total	**33**	**100**

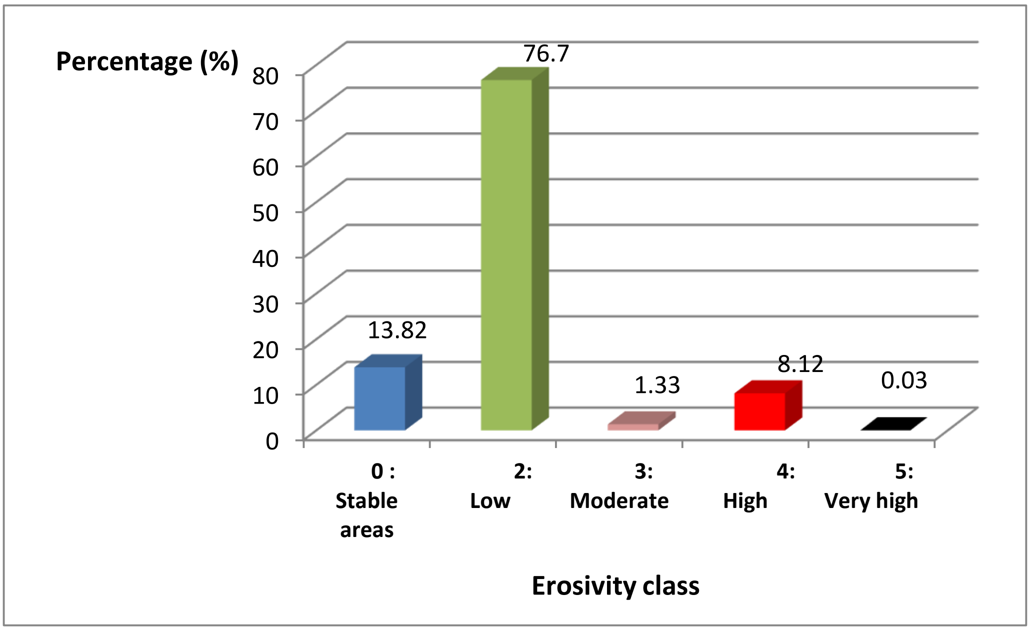

Figure 0.8: Distribution of erosivity classes of Boufekrane watershed

3.2 Descriptive Approach

From personal communication, it became apparent that two types of on-site erosion forms exist in Boufekrane: Gullies and sheet erosion. Gullies are formed at a distance of five meters of radius around secondary river basins and at a distance of height meters of radius around the main river basin (El Garouani; 2017). Sheet erosion are found to develop everywhere except in stable areas. This operation was made through ArcGIS by using a specific geoprocessing tool called 'Buffer' in Arc Toolbox spatial tools. Buffers around main and secondary river basins correspond to gullies, while the buffers the rest of the watershed is affected by sheet erosion except stable areas (housing and roads).

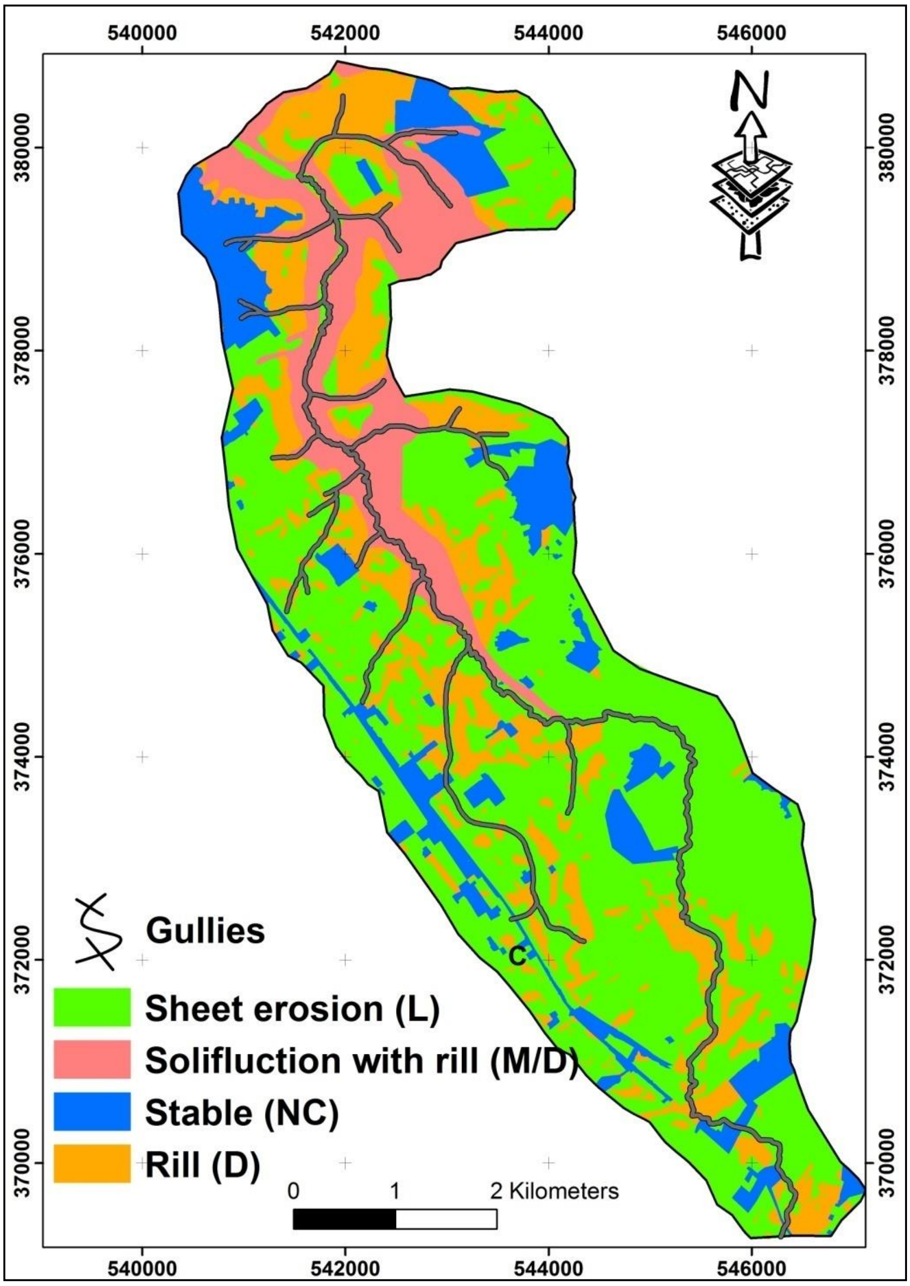

Figure 0.9: Map of actual erosion forms in Boufekrane watershed

The obtained results of actual erosion forms show that sheet erosion affects 18.35 km^2 of lands, accounting for 55.61% of the total surface. Rill erosion occupies 5.33 km^2 (16.15%). Solifluction combined with sheet erosion (M/L) cover 4.10 km^2 accounting for 12.42%. Gullies which are the most aggravated erosion form only affect 0.28 km^2 of the land and account for 0.85%. Table 4.7 shows different forms of erosion that occur in Boufekrane.

Table 0.7: Percentage of actual forms of erosion in Boufekrane watershed

Erosion	Area (km2)	Percentage (%)
Sheet erosion (L)	18.35	55.61
Rills (D)	5.33	16.15
Gullies (C)	0.28	0.85
Solifluction and rill (M/D)	4.10	12.42
Non classified	4.94	14.97

3.3 Consolidated Approach

Results of the final phase of soil risk assessment shows that sheet erosion with low erosivity ((2) L) is the most predominant form of erosion affecting lands in Boufekrane watershed. It affects 55.61% of the total affected area and is found everywhere in the watershed. This erosion form directly affects productivity of soils with a greater threat for those which are cultivated. It appears in areas characterized by low slopes and stable soils (cemented compacted). Rills are in turn predominant in areas with moderate to high slopes. They are divided into two erosivity levels: Rill with low erosivity ((2) D) affects 4.93 km^2 which accounts for 14.94% of the watershed area. (3) D represents rills with moderate erosivity. This erosion only covers 0.4 km^2 (1.21%). Solifluction with rill of low erosivity ((2) M/L) accounts for 3.46% whereas ((4) M/L) accounts for 8.96% of the total watershed. They mainly affect soils where marls are predominantly represented. Spatial distribution of erosion (consolidated map and erosion trend map) showed that solifluction combined with sheet erosion develop with a trend of generalized degradation towards an irreversible state, which can pose a threat of sedimentation in El Gaada dam. Gullies are less represented. It was found that gully with low erosivity covers 0.19 km^2 while gully with high erosivity covers 0.09 km^2. They are the most aggravated on-site erosion forms. According to importance of erosion causative factors, erosion forms vary from low to important intensities. On-site erosion descriptive map showed that large gullies are found at a distance of six (6) of radius around the main river basins while small gullies develop around the secondary stream at a distance of three (03) meters of radius.

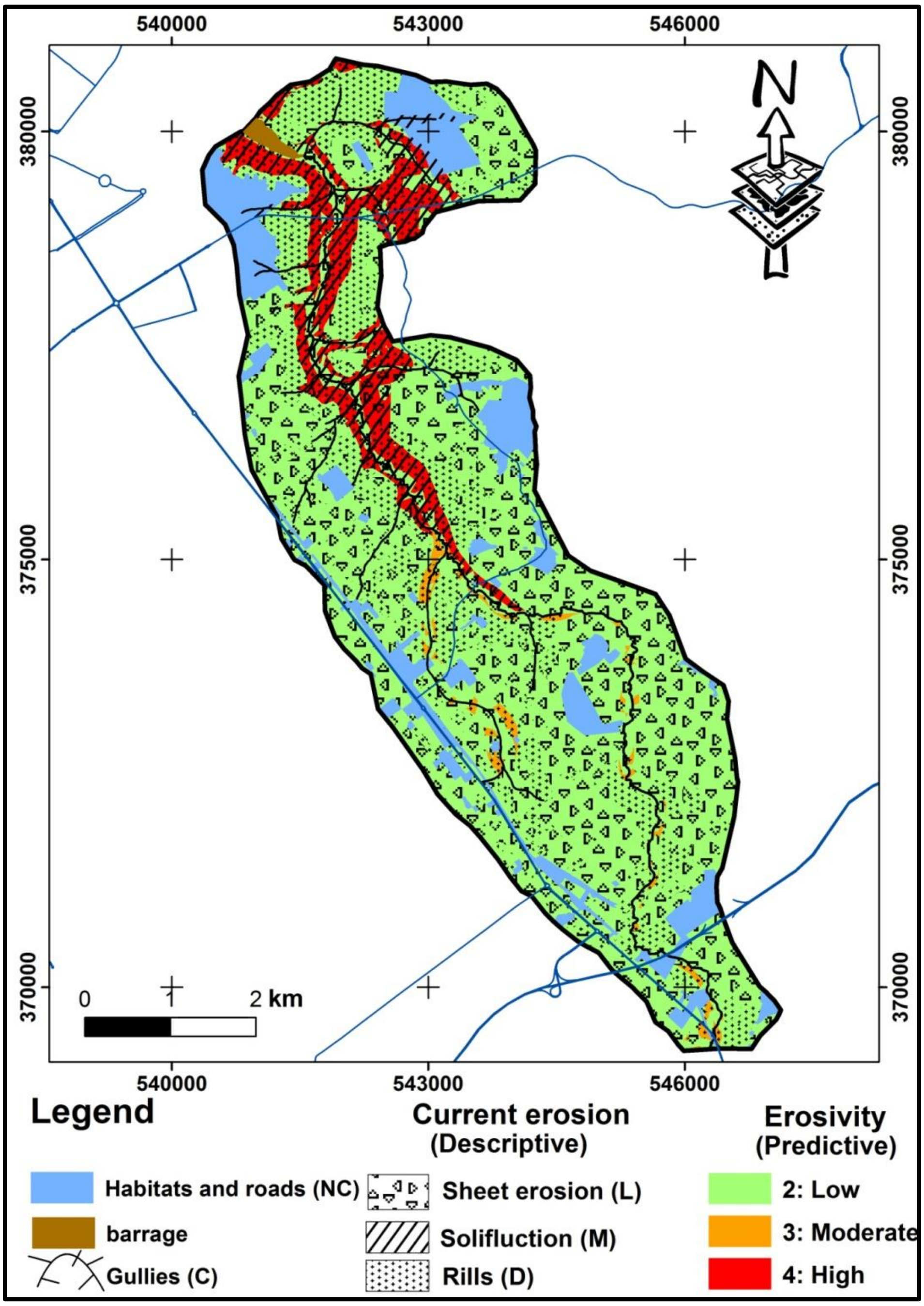

Figure 0.10: Consolidated map of Boufekrane watershed

3.3.1 Soil Erosion Expansion Trends

From analysis of soil erosion expansion trend map, one can argue the following observations:

- Grade 1 which refers to a trend of stabilization, regression or limitation of erosion process expansion is found to occur when erosion forecasts expect a low erosive states and field check shows a minor erosion actual form (sheet erosion or rill).
- Grade 2 referring to a trend towards a localized expansion or intensification of the erosion process appears when predictive analysis expects a notable to high erosive (erosivity 3 and 4) state but on-site erosion forms are of minor degree (sheet erosion or rill). In other words, there are other factors not taken into consideration in this particular study but tend to hinder processes of erosion.
- Grade 3 refers to generalized expansion or intensification of erosion process. In this case, preliminary studies forecast a low erosivity but observations show important current on-site erosion. Once again, other factors would accelerate erosion processes.
- Grade 4 occurs when predictive studies coincide with on-site descriptive mapping. Previsions predict a high level of erosive state and coincide with actual erosion forms. This grade refers to a major erosion process with a trend of generalized degradation towards an irreversible state. It is apparent from figure 4.10 that risk of sedimentation in El Gaada dam is very high. This is accounted for its proximity to areas with the highest erosion expansion trends (grades 3 and 4) as illustrated in figure 4.11.

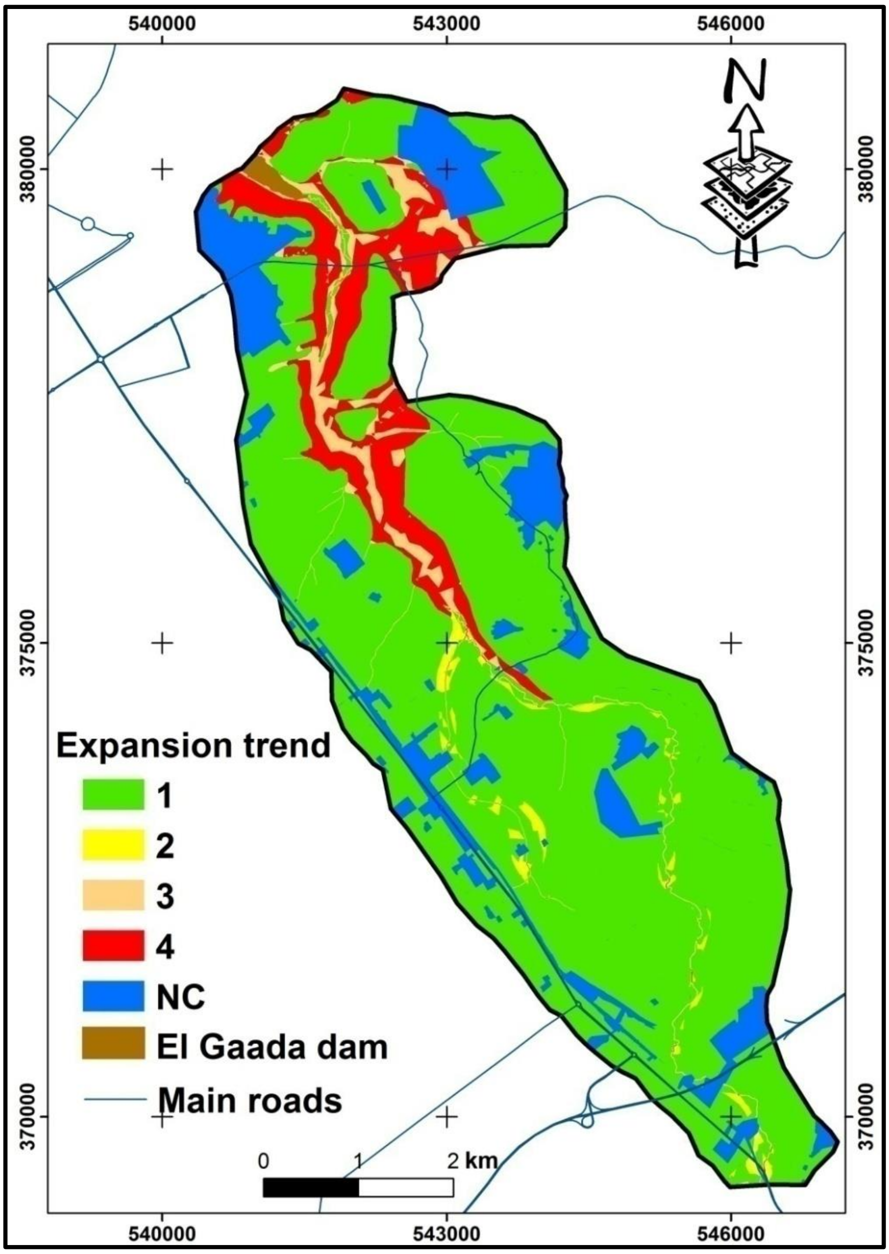

Figure 0.11: Rate of erosion expansion for unstable area

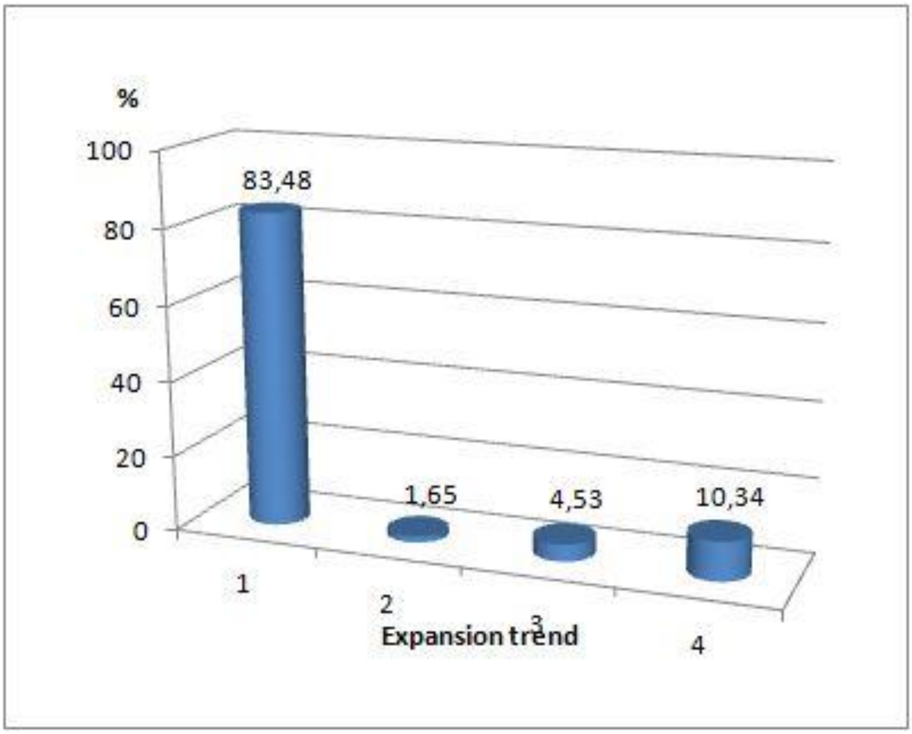

Figure 0.12: Percentage of erosion expansion trend in Boufekrane watershed

3.3.2 Soil Erosion Causative Factors

a) Types of cultures and cultivation practices

Given that Boufekrane is dominated by agricultural activities, types of culture and practices of cultivation are the most predominant erosion factors. Analysis of erosivity database showed the role they play in erosion processes. In fact, it was found that the highest erosivity state (4) is found only in agricultural areas (arable and cultivated). Arable lands covered by cereal cultures are more vulnerable to erosion risks compared to cultivated areas (olives and fruit trees). 86.6% of lands of high erosivity (grade 4) are covered by arable lands whereas that of cultivated lands accounts for only 13.50%. Arable lands are more vulnerable to erosion compared to cultivated areas due to combined effect of slopes and low vegetation density: Data processing and cross-tabulations of slopes and land use showed that 52.04% of arable lands are grown on low slopes whereas 69.66% of cultivated lands are grown on low slopes. Conversely, 30.17% of cultivated lands are grown on high slopes whereas 47.80% of arable lands are grown on high slopes. Moreover, analysis revealed that 99.68% of arable lands are of very low vegetation density while 90.93% of cultivated areas are of very low vegetation density. In other words, arable lands are poorly covered compared to cultivated lands. This tends to intensify and accelerate rainfall-induced erosion processes.

3.3.3 Lithofacies

Erosivity map have shown that downstream of Boufekrane watershed is more affected by erosion than upstream. Susceptibility of downstream to erosion resides in dominance of this area by deeply altered soils which are less cohesive and thus more sensitive to mechanical erosion processes (detachment and transport by water). Cross-tabulation of lithofacies and erosivity data showed that 99.36% of 4-grade erosivity develops on deeply altered and little resistant soils (fragility of class d). Spatial distribution of lithofacies shows poorly that developed and marls soils are dominant in areas presenting a high risk of erosion (downstream) which makes it more vulnerable to erosion rainfall-induced soil erosion. In fact, poorly developed soils and marls are less cohesive soils and thus, they tend to be easily detached and transported by water. Their fragile cohesiveness is due to their poor content of organic matter, low permeability and high percentage of fine particles. As a result, there is low infiltration of water into the soil which generates runoff and soil removal by water. Conversely, dominance of cemented conglomerates and weakly compacted rocks in upstream makes the soil more resistant to erosion. Those soils present a stronger cohesiveness due to high content of coarse particles.

3.3.4 Land use / change

Globally, Boufekrane watershed is experiencing an intensifying land use. Comparison between Normalized Difference Vegetation Index for the years 1987 and 2016 enabled understanding of the role played by land use change in erosion process expansion. Figure 4.13 shows a considerable decline of vegetation cover in 2016 with a maximum NDVI estimated to 0.45 while it was estimated to 0.56 in 1987. This loss of vegetation cover partly results from a generalized urbanization process. Consequently, increase of urbanized areas in turn leads to intrusion of riparian populations which is accompanied by consequent degradation of natural resources including forests (deforestation, bush fires, etc...). It is interesting to consider that decline in vegetation cover is accentuated in downstream (northern part) where slopes are relatively lower which tends to contribute to intensified agricultural activities. This explains the generalized increase of Utilized Area of cultivated areas (cereal crops and fruit trees) as well as unsustainable human practices (overgrazing, bush fire, deforestation, etc...) in Boufekrane. Conversely, it is also interesting to consider that in the upstream (southern part), the erosive state is lower because loss of vegetation is relatively lower. This can be explained by the fact that in this part of the watershed, altitudes are mainly dominated by high elevations which makes unlikely settlements of populations, and thus reduces negative impacts of human practices (deforestation, bush fires, etc...).

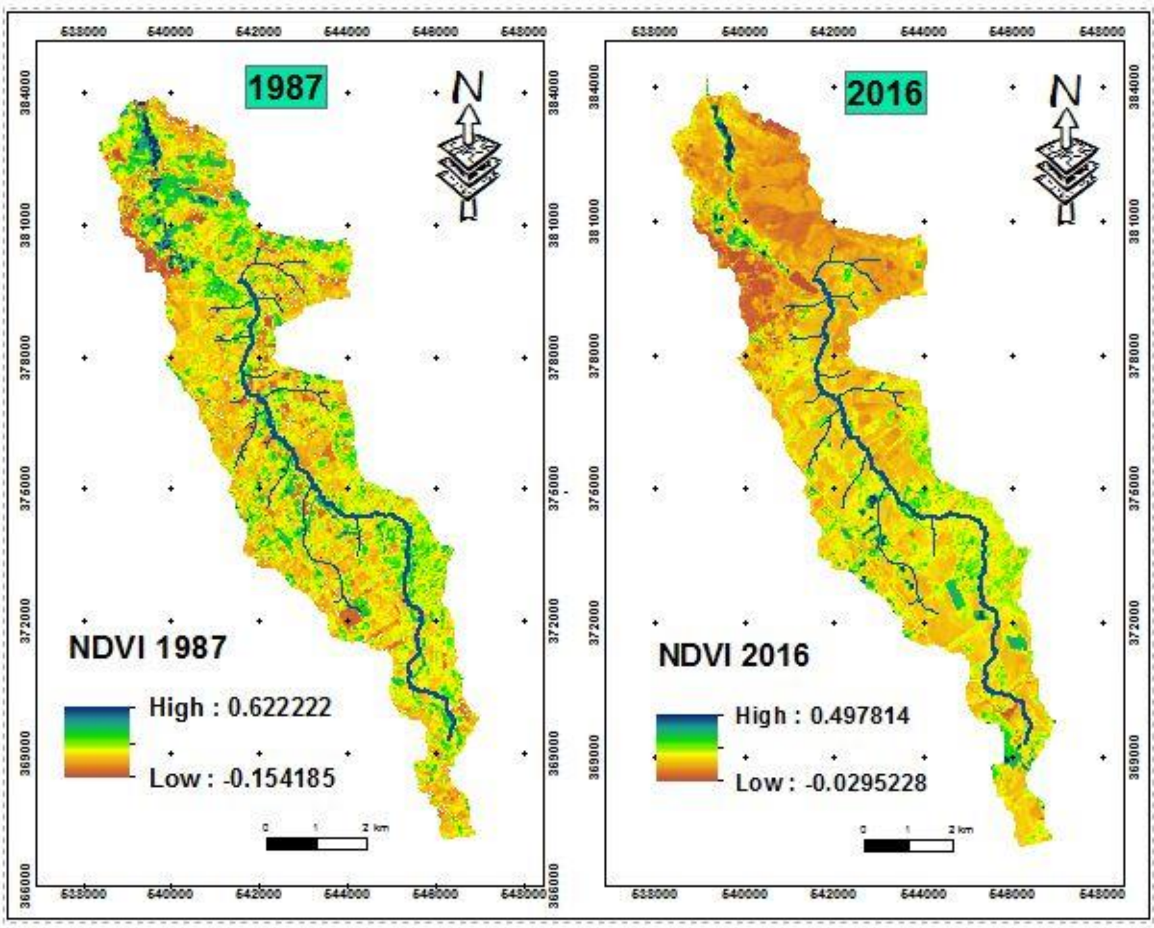

Figure 0.13: Land use change of Boufekrane for the years 1987 and 2016 (LGRES, 2017)

3.4 Trend Analysis

Despite erosion trend is generally in recession or limitation, it must be acknowledged that minor forms of erosion are in increased extent over the entire surface of Boufekrane watershed. Expansion of erosion processes results from degradation of the vegetation cover, which is recognized as an important stabilizing and fixing soil factor against erosion. This degradation of vegetation cover was confirmed from analysis of land use change and comparison of Boufekrane land use behaviour between the years 2006 and 2017. Ouazzani (2007) reported that in 2006, non-cultivated areas accounted for 7.03% while olives and fruit trees covered 24.49% and cereals covered 67% of the total areas. In 2017, non-cultivated areas are found to cover 1.06% of the total watershed area, while cultivated areas including fruit trees and olives account for 29.79%, and cereals account for 55.52% of the watershed area.

3.4.1 Erosion risks

The spatial distribution of erosivity states showed that high erosion occurs mainly in the downstream part of the watershed where El Gaada dam is located. In other words, risks of sedimentation are high. High erosion risks exist wherever slopes are important: Analysis of database showed that areas of moderate to high erosivity are areas with significant slope steepness. Lithology is also a major factor determining the magnitude and importance of erosion risks: Erosivity is high everywhere where soil is poorly resistant, weakly compacted and highly altered, fractured or moderately altered.

3.4.2 Comparative study: PAP/RAC versus RUSLE

This comparative study between PAP/RAC and RUSLE does not aim at drawing conclusive observations on accuracy of PAP/RAC model or RUSLE model. This section just aims at identifying similarities and difference, this in order to show a certain convergence of results. Figure 4.14 shows a spatial distribution of soil loss assessed by RUSLE model whereas figure 4.15 illustrates qualitative assessment of soil erosion by PAP/RAC. It should be pointed out that the quantitative assessment has not integrated influence of stable areas (Housing) in assessing soil erosion in Boufekrane watershed. From comparison Results show that more than 80% of Boufekrane watershed total area is of low erodibility, which means that Boufekrane is not highly vulnerable to erosion. This can be confirmed by RUSLE assessment study which revealed that 68% of the total watershed area has a relatively low erodibility factor (K) estimated to 0.11, while 19% of the total area has an erodibility factor of 0.27. Despite distinctions between the models, both quantitative and qualitative approaches indicate that arable lands occupied by cereals suffer at most from moderate to high grade of erosion. In addition, it is apparent from the two approaches that the northern part of the watershed (downstream) is more affected by erosion. The vulnerability of this part is due to dominance of steep slopes (3%-12% and 12%-20%) compared to the rest of the watershed, as confirmed from the slope map presented in figure 4.14. Another cause resides in and dominance of vertisols which are found to be more sensitive to mechanical erosion processes.

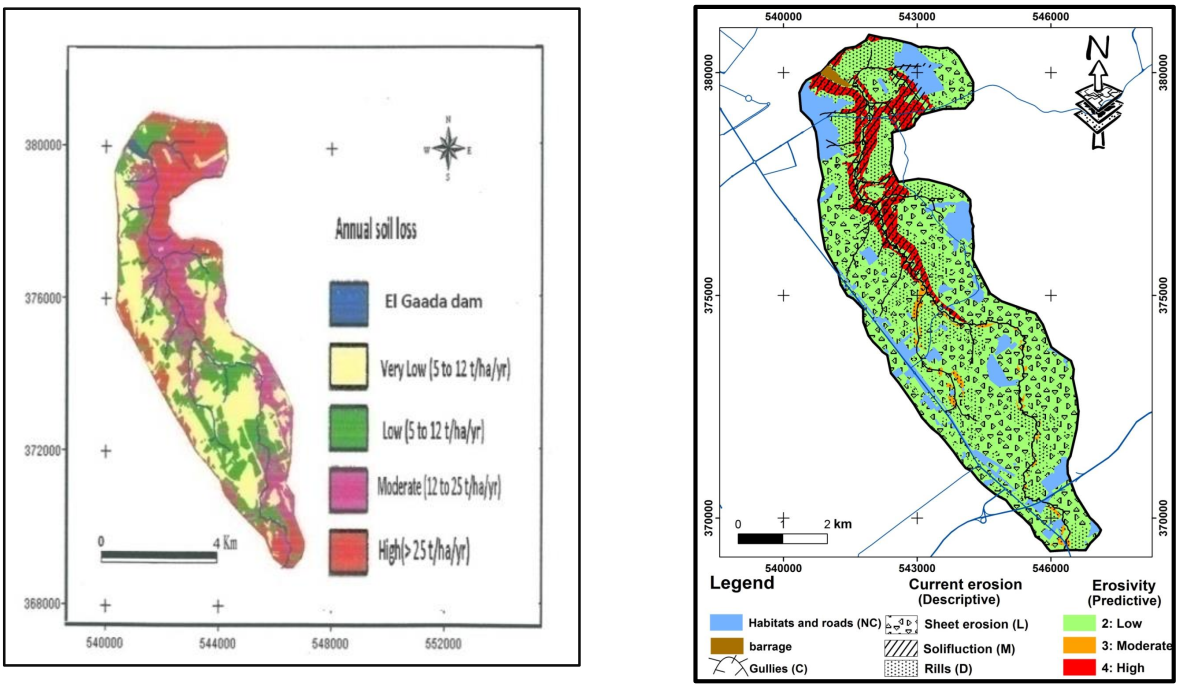

Figure 0.14: Soil erosion assessed by RUSLE model and PAP/RAC model

CHAPTER 5

GENERAL CONCLUSION AND RECOMMENDATIONS

4.1 General Conclusion

The use of GIS and PAP/RAC model in the current study was proved to be useful in assessing soil erosion risk in Boufekrane watershed. Sheet, rill, solifluction and gully were found to be the most common forms of erosion in the watershed. Major causative factors of erosion risks were found to be low vegetation cover, soil friability and low to moderate slope steepness. Erosion in Boufekrane is therefore mainly due to low vegetation cover density and to a lesser extent by slope steepness. El Gaada dam was found to have a high risk of sedimentation due to erosion. Moreover, analysis of erosion expansion has shown that El Gaada should be considered as a priority for action in order to prevent from a quick and premature sedimentation of the dam. Comparison of results obtained from PAP/RAC and other models e.g. RUSLE, indicate that the former model has a good capability of identifying onsite erosion forms. However, PAP/RAC model is limited to establish seasonal pattern of erosion in Boufekrane watershed. In addition, PAP/RAC does not consider climatic data, which tends to hinder its accuracy in assessing and evaluating soil erosion by water. The challenges of its applications opens further questions in research fields to improve its accuracy.

4.2 Recommendations

The final output map can be an efficient tool for erosion control and serve as basis for land management planning in Boufekrane watershed. Field reconnaissance surveys with remote sensing application could significantly improve results of site-descriptive analysis in further studies. Finally, accuracy of PAP/RAC model can be improved by taking into consideration other parameters such as rainfall, season variability (summer, winter, and spring) and population.

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ANNEX: GLOSSARY

Erodibility: It expresses the susceptibility of a soil to erosion. In other words, it refers to the soil resistance to erosion. For instance, at equal conditions (slope steepness, vegetation cover, etc…) clayed soils are less erodible that silty or sandy soils. Assessment of soil erodibility can be based on various factors depending on specific conditions even though there is no agreement up to date on how to measure it.

Erodibility map: It simply shows the spatial distribution of erodibility of a given area. Within the PAP/RAC methodology, it is obtained by overlapping slope and lithological maps.

Erosion: Here, 'erosion' refers to soil. It is a slight or important removal of soil by erosive agents like water, chemical compound, ice, wind or by gravity, and involving different processes (detachment transport, land movements…)

Erosion risk: This term is used when one wants to express the likelihood or probability of erosion process to occur or develop in a given area. Its assessment is based on evaluation of factors recognized to influence erosion.

Erosivity: Ability or potential power of erosive agents such as gravity, wind, water, ice or chemical compounds to cause erosion. In rainfall-induced erosion, raindrop mass, runoff kinetic energy (velocity) and rainfall intensity are found to be the most important influencing characteristics of erosivity.

Erosivity map: It exhibits the spatial distribution of erosivity status in a given area.

Erosion status: Assessment of both actual and potential erosion status takes into accounts information like topographical data, pedological and geological characteristics, land use and vegetation cover of the study area. However, rainfall and other climatic data are not considered while assessing the erosion status of that area.

Erosion expansion trend: Predictable trend of development or stabilization of an erosion process based on its nature, intensity and/or spatial expansion.

Gully: Form of erosion that is highly noticeable and characterized by deep digs due to important ablation and removal of soil due to large channels of water flows. Its depth varies up to 10 to 15 meters (in cases of very deep alluvial gullies). It affects the quality of water bodies and can cause dam siltation. Control of gullies is costly and can require strong operation skills. Gully development stalling measures include vegetation fencing, protection masonry structures.

Lithofacies: In geology, it refers to physical characteristics of a sedimentary layer, but can also evoke the organic and mechanic aspects of a soil.

Rill erosion: Erosion form due to removal of soil caused by concentrated surface runoff. Traces of erosion in ditches can be masked by simple cultivation practices. In agricultural areas, a rill can turn into a gully in absence of management and control measures.

Sheet erosion: Form of erosion characterized by removal of thin soil layer due to surface water runoff.

Solifluction: Type of erosion that is mainly caused by gravity or saturation by water. Heavy precipitations can easily trigger it.

Soil protection level: It reflects the vegetation protection of an area. In the PAP/RAC guidelines, the map of soil protection aims at giving a spatial distribution of low to high vegetation cover degrees and consequently enables an identification of black areas which require quick interventions to restore the vegetation cover (reforestation and stabilization measures).