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HYDROUS EROSION IN THE CATCHMENT AREA OF THE WADI LARBAA (RIF MOUNTAINS, MOROCCO): AGENTS, PROCESSES AND MODELING

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Key words : Hydrous erosion, modelling, Rif Mountains, Wadi Larbaa, Marocco.

Abstract. The watershed of Wadi Larbaa, in the Prerif area at the north of Taza, is a fragile and vulnerable milieu, where water erosion is causing annually important loss of land (soils) and excessive production of sediments. The structural setting is characterized by the predominance of soft materials, mainly marl, in a turbulent structure. The fragility of materials and their susceptibility to erosion are all the more important as most land is bare and exposed to direct morphogenic effects of rainfall events. The human pressure is spectacular in the area. The ancient settlement and early development of the land, based mainly on cereals and livestock have destroyed natural vegetation. This inherent vulnerability of the environment is exacerbated by a marked concentration of extreme weather events causing in time various erosion processes. Gully erosion is very active and it is responsible for most of the sediment transfer in the region. Landslides are very diverse. Their later evolution by gulling processes, evacuates large quantities of sediments from moving masses. Soil loss is consequently important; quantification tests show that the average loss in soil clearly exceeds the tolerance thresholds known in the Rif Mountains. In the case of the Oued Tleta sub-basin (situated in the upper part of Wadi Larbâa), the weighted average loss of the surface is of 61.42 t / ha / year. Maximum losses according to the land use are estimated at 129.12 t / ha / year as recorded level on wastelands and grazing lands. This study presents the main results obtained by means of field measurements and the quantification of erosion in this catchment area. It includes the factors involved in hydrous erosion in the studied area, in order to identify the main processes acting on slopes.

Introduction

The Rif mountains retain important human densities, despite migration. The human footprint, to which the different forms of land use are linked, explains, in

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large part, the variability of the phenomena of environmental degradation and the accelerated erosion (Tribak, 2007; El Aroussi et al., 2011). The Wadi Larbâa catchment is situated in the semi-arid climate in the northern part of Morocco. It is characterized by a dissected relief with an important extension of marl substrates. Thus, crop lands are subject to an intense dynamics of erosion that causes an annual impressive soil loss. Observations made during the unusually wet periods, show distinct aspects about the erosion processes. The erosion's quantification tests at some basic incisions or by the application of the universal equation of soil loss (RUSLE model), show huge losses in some sectors that exceed the tolerance threshold. The main objective of the paper is to study the different parameters that control the spatial distribution of processes and terms of hydrous erosion and to explain the huge annual loss of soil and sediments that are discharged to the main drains of the basin.

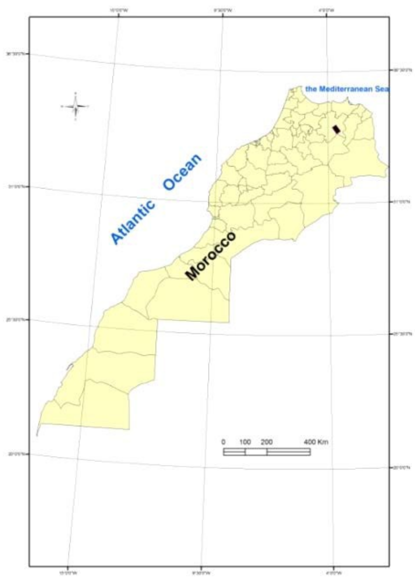

Fig. 1 - Location of the studied catchment area (Larbâa River)

Studies and field observations conducted in the region allowed us to locate the different forms of erosion, to monitor their evolution and to compare the results obtained by using the GIS and remote sensing tools. The quantification of soil loss was performed either by direct actions in plots (rills and gullies or by using an empirical model. The RUSLE empirical model allowed us to assess the average annual rate of erosion over the entire sub-watershed of Wadi Tleta, depending on the distribution of rainfall severity, the erodibility of soils, topography, land use and crop management practices. Infiltration measurements were also conducted on some slopes, taking into account land use parameters. Our approach relies equally on the use of remote sensing data for understanding the spatial differentiation factors of erosion (land use, plant cover, ...) and the use of the geographic information system (GIS) for the analysis and modeling of erosion and sediment deposition. Among the advantages of using satellite images in this analysis, there is its ability to uncover land-use and vegetation changes over time in the sub-basin of Wadi Tleta. In addition, this approach permits an ordinal ranking of soil loss and deposition in areas with minimal data bases. Thus, it is possible to compare landscape conditions for specific time periods and to document these changes as they occurred. For this study, four land use/vegetation cover maps for the 15 year period from 1987 to 2002 were developed. From these data, soil loss patterns are inferred by inputting these data into the RUSLE model.

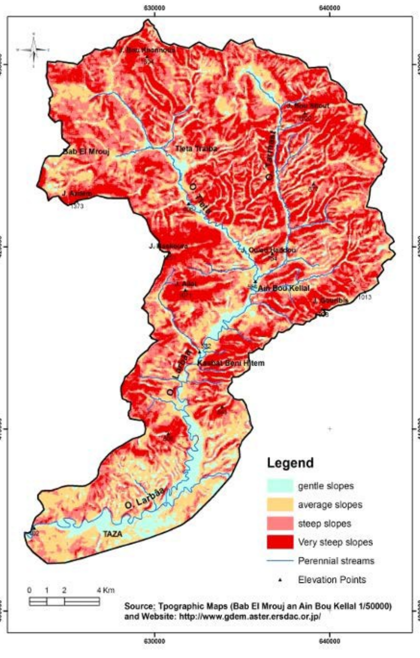

Fig. 2 - Slopes of Wadi Larbaa

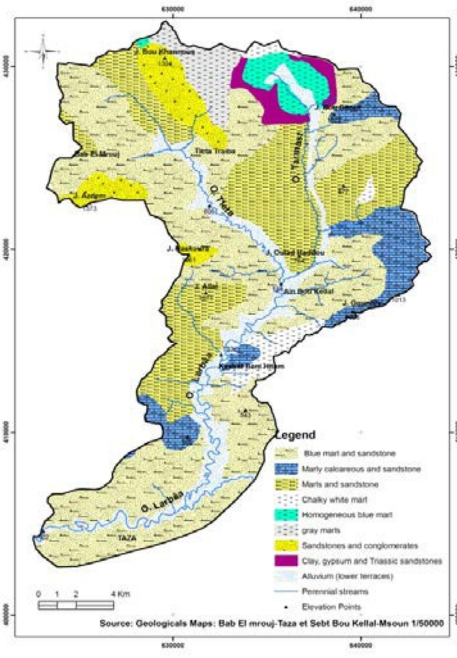

Fig. 3 - Lithological map (Wadi Larbaa)

A fragile environment predisposed to erosion hazards. The studied catchment area is part of the Eastern Prerif in the North zone of Taza, where hills and low mountains offer irregularly shaped sides of slopes (Fig. 2), related to the complexity of the structure and the importance of quaternary legacies. The predominance of soft materials, mainly marl or marly limestone, in a turbulent structure, is an important factor that determines a rapid and disorderly slopes evolution. The marl series, dating from the end of the Tertiary geologic period, are widespread (Leblanc, 1979). They are partly overlain by sandstones that arm especially the high mountains of allochthonous units (Fig. 3). The derived soils mainly belong to classes of soil erosion slightly evolved on steep slopes, and calcimagnesian soils with vertisols in the less rugged area (Tribak, 2000).

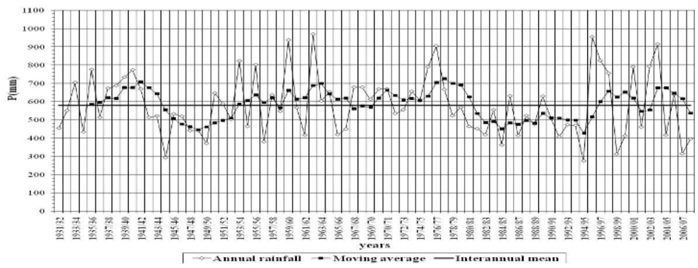

Fig. 4 - Variability of annual rainfall (Taza station, 1931 - 2007)

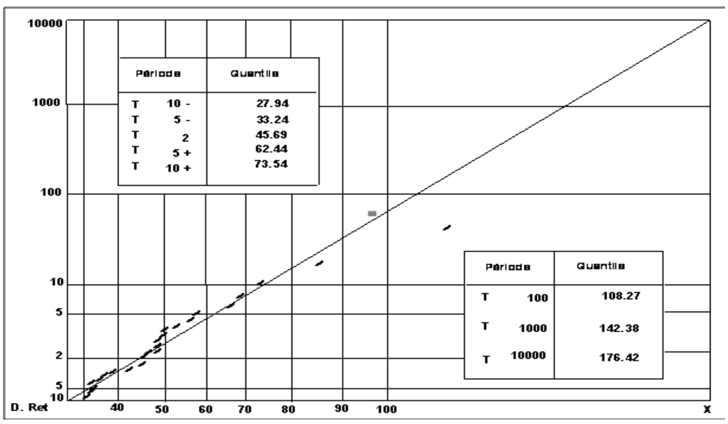

Fig. 5 - Maximum Daily Peaks (Taza station, 1979 - 2007), Gumbel Adjustment

The region's climate is marked by strong seasonal contrasts and sharp irregularities in rainfall. The total annual rainfall is, depending on the station, between 390 and 740 mm (Fig 4) and does not reflect seasonal and interannual variability of rainfall or aggression. Rainfall events are generally brutal and the heaviest rains are concentrated in a few days of the wet season. The close succession of exceptional rainfall events is a source of risks to these environments.

These events produce very large quantities of water in a few days or in a few hours, with very high instantaneous intensities. They are directly involved in the mechanisms of erosion and flooding and thus act on the effect of torrential waters in the rivers. Their occurrence is related to thermo-convective rainstorms that occur in the late summer or early autumn. Significant amounts of rain may fall in some hours, just after long periods of summer drought. On 29/09/1997, a rainfall storm of extreme violence supplied 68 mm in only 40 minutes, giving an average intensity of 102 mm/h, with peaks of intensity probably exceeding 120 mm/h (Tribak, 2007).

They also can be linked to very wet consecutive days related to Atlantic meteorological disturbances. The daily exceptional peaks, whose frequency is large enough, can reach very significant records. Very demonstrative examples can be cited: 101 mm on the 30th of January 1987 (33% of the monthly module in the Had Msila station) and 113 mm on the 14th of March 2004 (61% of the monthly module in Taza station). The frequency analysis of the daily maximum peaks shows an increase in frequencies for heavy rains located between 33 and 76 mm (Fig. 5). Thus, they correspond to return periods ranging from 2 to 5 years depending on the different stations (Tribak, 2007).

High horary intensities, characterizing some of these rainfall events, can produce large runoff coefficients and exacerbate the erosion processes. They are generally very high for short periods, but weaken once the times are getting longer. The maximum intensities in 5 minutes reach very important records: 82.2 mm/h on January the 29th, 1986 and 55.5 mm/h on November the 7th, 1987. However, the maximum intensities in 60 minutes rarely exceed 10 mm / h. Exceptional peak intensities greater than 100 mm /h correspond to violent storms of early autumn and they cause considerable damage, as was the case on the 29th of September, 1997: 102 mm/ h was recorded (Tribak, 2006b). Erosivity indices, calculated using the equation of Arnoldus, reflect significant rainfall aggressiveness but, they are highly variable in space and time depending on the position of stations and annual rainfall amounts received. It is in the range of 54.56 at Aknoul, 56, 66 at Tighzraine, 54, 57 in El Kifane, 101.6 at Taineste, 83.5, at Msila 92.4 to Echouyab, 94.4 at Marticha, and 76 in Taza (Tribak, 2000).

The human settlement is very ancient. The densities are still impressive, despite the reduction due to recent migration. They reach a peak of 100 inhabitants per km^2 with an average density of 76 inhabitants per km^2 for the whole region (Tribak, 2000). The human footprint and land conquests are spectacular. Most slopes are totally bare and cultured, with the exception of some reforested areas covering some mountaintops.

The analysis of the human influence and its impact on the Prerifain mountain, shows that various forms of land use explain to a large extent the variability of the environmental degradation. Overuse of cleared land, fueled by population growth, explains the expansion of farming into areas with steep slopes, which result in accelerated erosion in this fragile environment. Nevertheless, the rural decline that has recently affected many sectors is also a factor of environments instability. The tests of such influence on water infiltration and erosion processes are significant (Fig. 6 and 7).

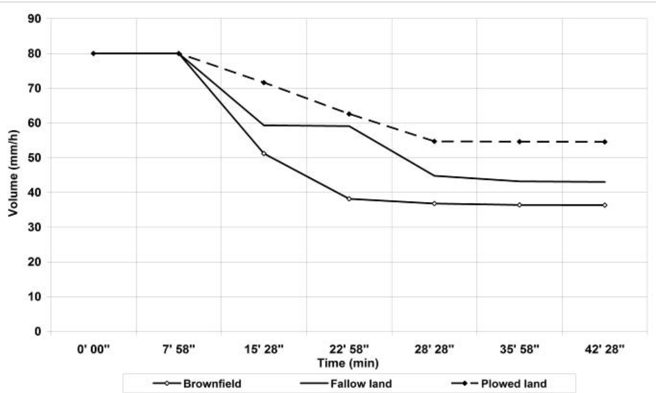

Fig. 6 - Evolution of infiltration according to land use on plots of calcimagnesian soils

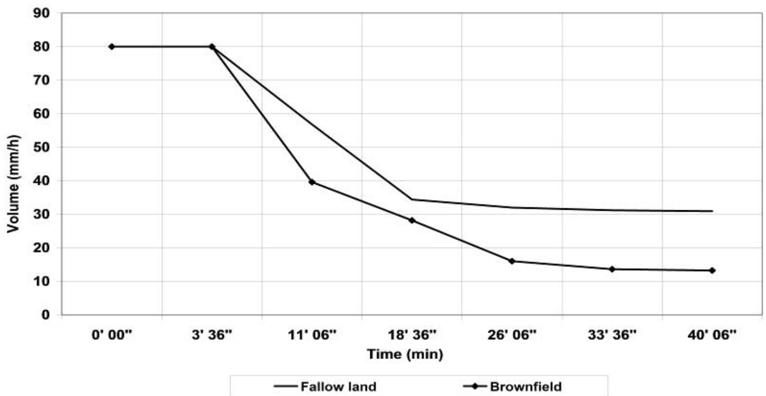

Fig. 7 - Evolution of infiltration according to land use on plots of less evolved soils

Rapid compaction of abandoned land or periodically fallow lands, in the absence of tillage favorable to infiltration, allows a concentration of runoff that contributes to the onset of dense networks of incisions. The surface degradation, which increases with time, controls in large part the nature of the flows. Simulations of rainfall conducted on abandoned land in the valley of Wadi Larbâa show that the runoff coefficients are very high (Fig. 6-7). Land loss, which is occasionally low compared to cultivated land, records however higher annual rates, due to the high frequency of runoffs along the year. Thus, fallow and abandoned lands (Brownfield) constitute a place of intense dynamic of erosion in the absence of basic maintenance and protection works (Tribak et al., 2008).

1. Process and erosion patterns

The interaction of anthropogenic and natural conditions, as mentioned above, is a factor of the accelerated rate of erosion dynamics. The area is prone to very intense erosion; almost barren slopes suffer from the impact of rainfall events and are subject to intense etching and runoff, resulting in a significant dilapidation (loss) of soil. Gullies settle preferentially on cleared and cultivated slopes (fig. 8, 9). They are more incised in sections where the superficial formations are very thick. They vary in size and intensity on the base of textural, mineralogical and chemical features of the affected materials, in the Miocene marls. The development of channels is also influenced by certain soil properties, such as their consistency, their ability to swelling and shrinkage, and susceptibility to dispersion (Gerits et al., 1987). Dispersive materials, rich in expansive clay (especially smectite) and containing gypsum and sodium are prone to the development of tunneling that turn into rills or developed gullies (Imeson et al., 1988; Tribak, 2000). Gullying processes can annually remove significant amounts of land to topsoil. Quantification tests based on the dimensions of linear incisions on the field after extreme rainfall events show huge ablation, especially on plots of less evolved soils and vertisols located on Miocene marl. The soil loss is estimated at about 140 t/ha/year (Abahrour, 2009).

Badland landscape features are widespread in the region; they grow on marl and marl sandstone rocks of Miocene. Because of the scarcity of vegetation, these environments are prone (are subjected) to the crusting of soils which enhance runoff and gullying processes on the slopes (Tribak, 2000). By their rapid evolution, they represent an important source of sediment evacuated to the main drains. The establishment of badland landforms seems to be very ancient in the region. C^{14} dating of deposits of a recent well-developed terrace near the landscapes of badland in the upper Wadi Larbaa basin is an argument that helps to estimate approximately the beginning of evolution of these phenomena. These deposits dated to 3571 BP show that the development of badland forms in this area probably corresponds to a recent episode in the Rharbien stage. The considerable thickness of these deposits, their silty texture and their color suggest that they are from the intensely gullied marly formations that line the river in this section of the basin. The probable appearance of badlands at this period would be related to climatic variations affecting the Rharbien stage that appears, according to Wengler, as an overall wet period interspersed with drier episodes during which erosion dominates. Nevertheless, the role of human impact can not be totally excluded; the major effect of climate variations have been compounded by a possible human presence and activity at that period (Tribak, 2000).

Fig. 8 - Gully on Miocene marl, evolving rapidly by various processes (solifluction, piping and, undercutting of banks)

Fig. 9 - Mudslide in the sandstone-marl alternations, the front part evolves through processes of gullying

Landslides phenomena are quite frequent in the region. They constitute accidents of large size, whose forms and mechanisms of evolution are complex. We can mention among these types of movements the mudslides and the flow slides. Their genesis is the combination of several factors: geometrical, related to the steepness of the topographic surface; structural, depending on the complexity of the structure and arrangement of rocks and lithological, related to the extension of marly lands whose rheological behavior is very supportive of solifluction. They cover areas which remain unproductive, and similarly, the later evolution of the displaced masses by gully erosion process results in production of sediments to the main rivers (Tribak, 2006a). The geotechnical characteristics of the Miocene marl, especially in the presence of swelling clays and dispersing elements, explain the diversity of these phenomena and their rapid evolution. Indeed, high levels of swelling clays (expansive clay, smectite) make them likely to absorb large amounts of water, resulting in a modification of their mechanical properties. Also, a fairly high content of dispersants (Gypsum, sodium), resulting in surface by formation of efflorescence salt, engenders as well a change in the volume of materials and their mechanical conditions. Geotechnical limits remain low enough, to explain the establishment and especially the rapid evolution of these phenomena. (Tribak, 2006a)

2. Soil erosion modelling

Maps of soil loss established in different basins of the region using the revised universal equation of soil loss Wischmeier (RUSLE) show both the extent of land loss in the basin and its great variability from one sector to another (El Garouani et al., 2003 and 2008). In the case of the basin of the Oued Tleta (situated in the upper part of Wadi Larbâa) the weighted average loss from the surface is 61.42 t/ha/year (Tribak et al., 2009). Maximum soil loss is estimated at 129.12 t / ha / year as recorded on wastelands and grazing lands (Tribak et al., 2009). It generally corresponds to Regosols and erosion in less evolved soils having little protection and located on steep slopes. Lands reserved for annual crops and tree crops also show a high susceptibility to erosion with annual soil loss of respectively 57.61 t / ha and 64.36 (t/ha/year), shows that in the eastern and southeastern portions of the basin, a net soil loss of 50 t $ha^{-1}year^{-1}$ occurs in these environments. This is related to an important extension of marls and sandy marls, highly sensitive to erosion processes (El Garouani et al., 2010). The land use categories in crop cultivation and mixed farmlands occupy a large proportion of the river basin. In the areas where these cultivations occur on moderate and steep slopes, net soil loss still occurs and these zones are of excessive erosion. But when the farming activities occur in the plain areas and valley bottoms, they

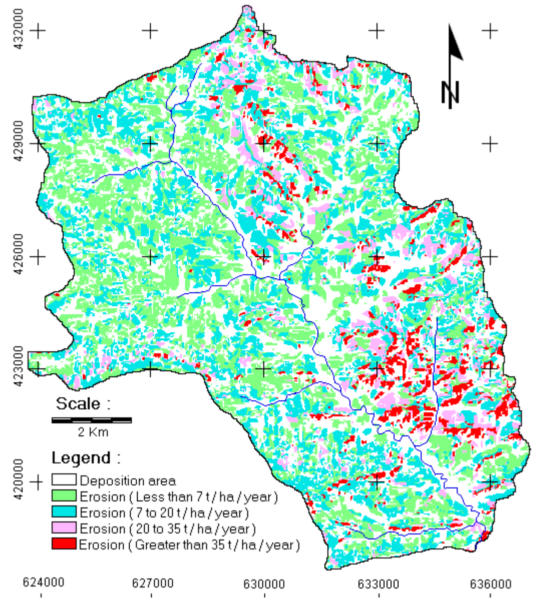

Fig. 8 - Map of annual mean soil losses in the sub-basin of the Tlata River (located in the upstream part of Wadi Larbâa)

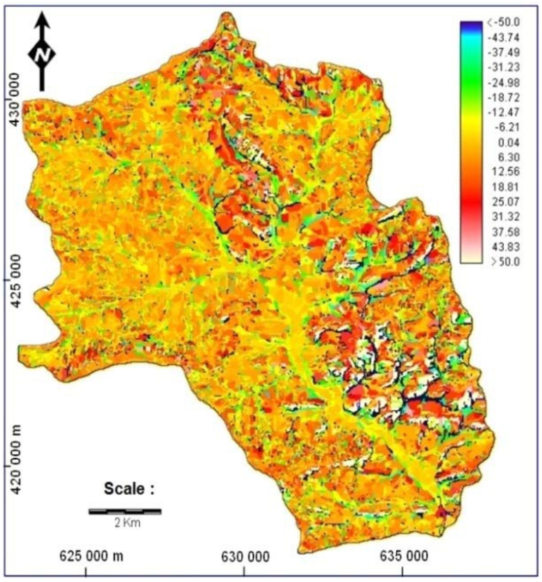

Fig. 9 - Net soil loss map established by RUSLE/SEDIMENTATION models (t/ha/year).

Tab. 1 - Average net soil loss-deposition by land cover calculated using RUSLE/SEDIMENTATION models (t/ha^{-1} year^{-1}). (El Garoauni et al., 2010)

Land use cover types	1987 Average net soil loss	1994 Average net soil loss	2000 Average net soil loss	2002 Average net soil loss	(1987–2002) General average
Badlands	24.69	30.83	25.58	33.81	26.23
Arable	–1.55	–1.69	–1.55	–1.30	–1.52
Arable/arboriculture	–5.50	–6.62	–5.66	–2.63	–5.10
Olive trees	–0.10	0.66	0.85	0.59	0.50
Reforestation	0.38	–1.62	–4.93	2.42	–0.94
Spare forest	1.67	1.81	2.69	1.94	2.03

experience net deposition (negative values - table 1). The badlands categories are likewise areas dominated by steep slopes.

Given that these zones occupy approximately 9.5% of the basin, the soil loss data for the sub-basin of the Tlata River (located in the upstream of Wadi Larbaa) indicate that these areas must be degrading and they are likely to experience declining yields on the short term and likely go out of production unless interventions occur shortly (El Garouani et al., 2010).

3. Discussion

The field work observation and the soil erosion quantification studied in the area show that the intensity of erosion and consequently the significant soil loss within the basin, rely heavily on the important expansion of fragile marly formations, combined with a strong anthropogenic influence. The predominance of clay and silt in most soils, derived from the marly formations, makes the infiltration regime very complex. The ability of a wide range of soil to swell and desiccate (shrinkage) and their sensitivity to the phenomena of crusting, influence strongly the conditions of soil infiltration. Closure of cracks in clay soils leads to surface sealing and increased runoff, favorable to the development of gullies (Bryan, 1987). Structural degradation, due to rain, affecting the upper layers of fine textured soils, can cause a positive waterproofing to runoff. The crusts, formed under the action of rain, can change the surface water regime and greatly reduce water infiltration into the soil (Valentin et al., 2005). In the basin, they affect most of the soils, due to the predominance of silt textures or clay loam, although their importance is variable from one soil to another, depending on the variability of particle size characteristics. This greatly reduces infiltration rates that record low values, to less than 20mm/h on less evolved soils (Fig 6), while runoff coefficients remain very high.

Moreover, the presence of dispersing elements, such as gypsum and sodium, remains in favor of piping, suffusion and solifluction processes, which are even more important if these soils contain high proportions of clays. The structural arrangement between rocks of different nature within the same watershed influences clearly the morphology of slopes and controls the movement of water in different sections. Lithological discontinuities within marly sandstone formations are favorable to the initiation of complex landslides that mobilize huge masses of materials especially in the middle and basal sections of slopes, where detritic stocks are considerable (photo 2). This fragility of materials and their susceptibility to erosion are more important as most fields are bare and directly exposed to the erosive process. The antiquity of the settlement and the early development of the land, based mainly on cereals and livestock activities have virtually destroyed the natural vegetation protective of slopes. This explains, in a large part, the very high rates of soil loss on bare land under cultivation or overgrazing. The average soil loss across the basin records, in turn, important values well above the tolerance levels. For comparison, the average soil loss is estimated in the watershed of Wadi Nakhla in the western Rif to 65 t/ha/year in the field (Naimi et al., 2004) and 60 t / ha / year in the basin of the Oued Ouergha (Le Landais al., 1995), and 55.35 t / ha / year in the basin of Boussouab wadi (Sadiki et al., 2004).

Conclusion

The analysis of various parameters and the quantitative assessment of water erosion in this region of Prerif show great fragility of these environments. The intensity of hydrous erosion on this catchment area is explained by the prevalence of the marly grounds, the concentration of extreme rainfall events and the overuse of the land combined to deforestation of the steep slopes. Soils and superficial land mainly from marl are sensitive to many erosion patterns and processes. This is especially important when the land is almost totally bare (denuded) and cultured. The enormous soil loss recorded annually shows an interweaving of factors both natural and anthropogenic. The above mentioned average losses in soils clearly exceed the tolerance thresholds,, although they are around ablation rates recorded in some parts of the Rif mountains. This reflects the importance of accelerated erosion in the basin and the contribution of the various factors analyzed above. Nevertheless, it remains to note that these losses are unevenly distributed in space; areas heavily affected mainly reflect the barren lands where sloping stretch Regosols and less evolved soils of erosion derived from the Miocene marls. Badlands and gullies are the main source of the huge amounts of sediments discharged annually to Larbaa wadi and its tributaries; agricultural land and infrastructure are seriously threatened.

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